4

Structure and Function of Cells

CHAPTER OUTLINE

LOOKING AT LIFE

APPLICATIONS

HOW SCIENCE PROGRESSES

HOW SCIENCE PROGRESSES

HOW LIFE CHANGES

BEFORE YOU BEGIN

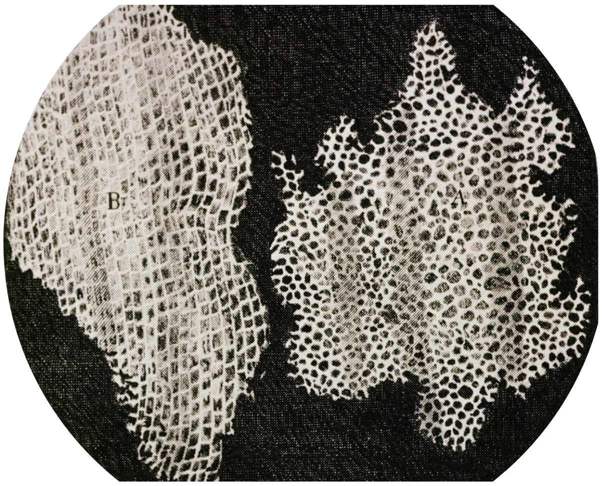
Take a few minutes to recall

The role of glucose and ATP as energy sources (sections 3.3 and 3.10)
How phospholipids form membrane (section 3.6)
The metabolic function of proteins in cells (section 3.7)
The function of DNA and RNA in cells (section 3.9)

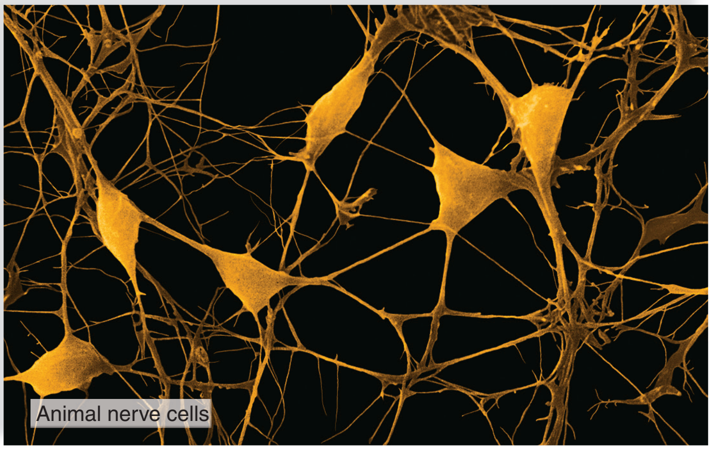
Cells: What Are They?

Imagine that you have never taken a biology course, and you are alone in a laboratory with a bunch of slides of plant and animal tissues and a microscope. The microscope is easy to use, and soon you are able to focus it and begin looking at the slides.

Your assignment is to define a cell. In order not to panic, you idly look at one slide after another, letting your mind wander. Was this the way Robert Hooke felt back in the seventeenth century, when he coined the word "cell"? What did he see? Actually, Hooke was using a light microscope, as you are, when he happened to look at a piece of cork. He drew what he saw like this:



Hooke saw almost nothing except for outlines, which we know today are the cell walls of plant cells. Similarly, you can make out the demarcations between onion root cells in the micrograph on page 61. After comparing these to the nerve cells below, you might conclude that a cell is an entity, a unit of a larger whole.



Once you had such a definition for a cell, you might be able to conclude that cells are present in all the slides at your disposal—as in all the micrographs on these pages. But it certainly would take a gigantic leap to hypothesize that all organisms are composed of cells, and this didn't occur until almost 200 years after Hooke used the term cell. You can appreciate that science progresses slowly, little by little, and that a theory, such as the cell theory, becomes established only when an encompassing hypothesis is never found to be lacking. Indeed, it was only when Matthias Schleiden always saw cells in plant tissues, and Theodor Schwann always saw cells in animal tissues, that they concluded, respectively, in the 1830s that plants and animals are composed of cells.

This chapter begins with an explanation of the cell theory and then considers the general characteristics of cells. The cell theory was formulated before the electron microscope was invented and before the biochemical techniques now used to study cells were developed. These improvements in technology tells us how the structure of cells is suited to carrying on the functions necessary to staying alive. These activities are common to all cells, and only in later chapters do we consider the specific functions of specialized cells.

Onion root cells

Rod-shaped bacteria

Euglena, a protist

The Cellular Level of Organization

All organisms are composed of cells, which are about the same small size whether present in an ant or a whale. Surface-to-volume relationships explain why most cells can be measured in micrometers, a unit of the metric system (see back endsheet). The two major types of cells—prokaryotic and eukaryotic—differ in complexity, but even so both contain DNA and have a cytoplasm enclosed by a plasma membrane.

4.1 All organisms are composed of cells

LEARNING OUTCOMES

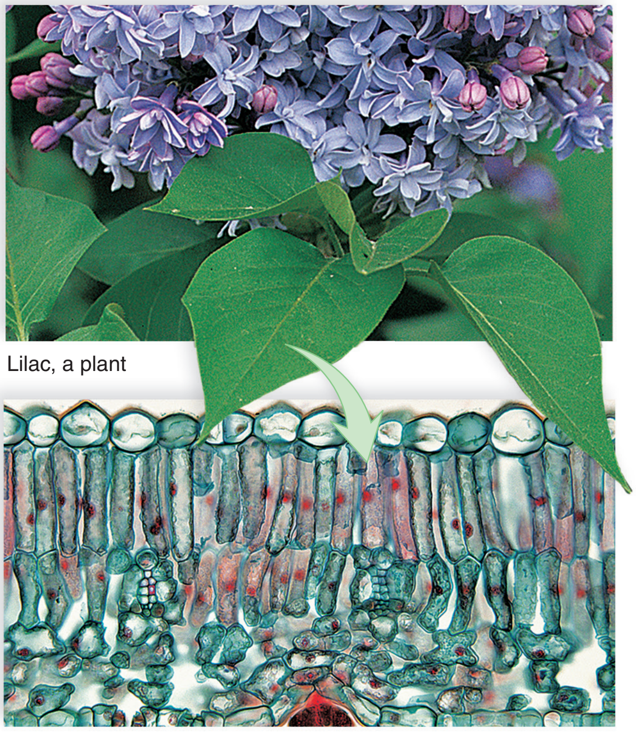
When you complete this section, you should be able to

1. List and explain three tenets of the cell theory.
2. Evaluate why cells are so small.

The **cell theory** states the following:

1. ***A Cell Is the Basic Unit of Life*** This means that nothing smaller than a cell is alive. A unicellular organism exhibits the characteristics of life we discussed in Chapter 1. No smaller unit exists that is able to reproduce, respond to stimuli, remain homeostatic, grow and develop, take in and use materials from the environment, and adapt to the environment. In short, life has a cellular nature. On this basis, we can make two other deductions.
2. ***Organisms Are Made Up of Cells*** While it may be apparent that a unicellular organism is a cell, what about more complex organisms? Lilacs and rabbits as well as other visible organisms are multicellular. Figure 4.1A illustrates that a lilac leaf is composed of cells, and Figure 4.1B illustrates that the intestinal lining of a rabbit is composed of cells. Is there any tissue in these organisms that is not composed of cells? For example, you might be inclined to say that bone does not contain cells. But if you were to examine bone tissue under a microscope, you would see that it, too, is composed of cells. Cells have distinct forms—a bone cell looks quite different from a nerve cell, and they both look quite different from the cell of a lilac leaf. Although cells are specialized in structure and function, they have certain parts in common. This chapter discusses those common components.
3. ***New Cells Arise Only from Preexisting Cells*** This statement wasn't readily apparent to early investigators, who believed that organisms could arise from dirty rags, for example. Today, we know you cannot get a new lilac bush or a new rabbit without preexisting lilacs and rabbits. When lilacs, rabbits, or humans reproduce, a sperm cell joins with an egg cell to form a zygote, which is the first cell of a new multicellular organism.

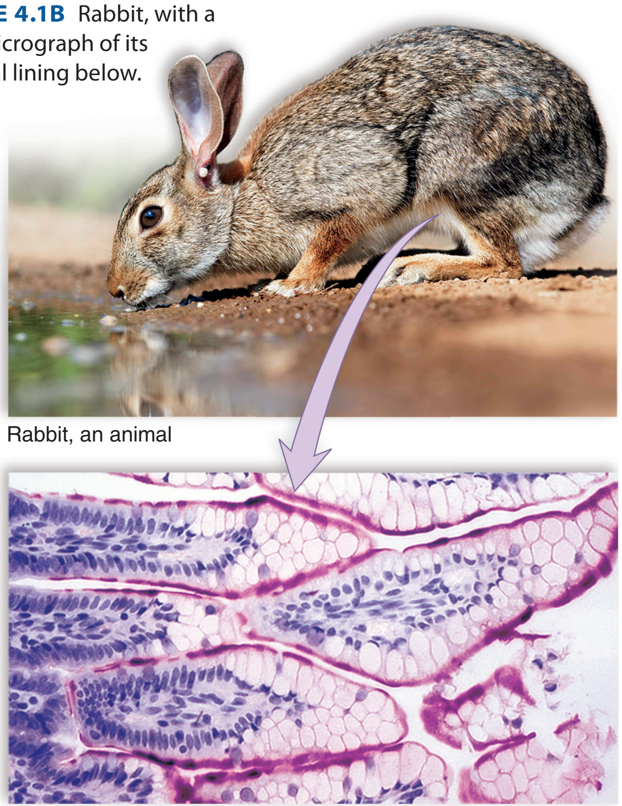
Cell Size Cells tend to be quite small. A frog's egg, at about 1 millimeter (mm) in diameter, is large enough to be seen by the human eye. But most cells are far smaller than 1 mm; some are even as small as 1 micrometer (μm)—one thousandth of a millimeter. Cell structures and biomolecules that are smaller than a micrometer are measured in terms of nanometers (nm). Figure 4.1C outlines the visual range of the eye, the light microscope, and the electron microscope using units of the metric system (see back endsheet).


Lilac, a plant

Micrograph of leaf reveals cells.

FIGURE 4.1A Lilac leaf, with a photomicrograph below.

FIGURE 4.1B Rabbit, with a photomicrograph of its intestinal lining below.


Rabbit, an animal

Micrograph of intestine reveals cells.

"Microscopes Allow Us to See Cells" on page 64 explains why the electron microscope allows us to see so much more detail than the light microscope does.

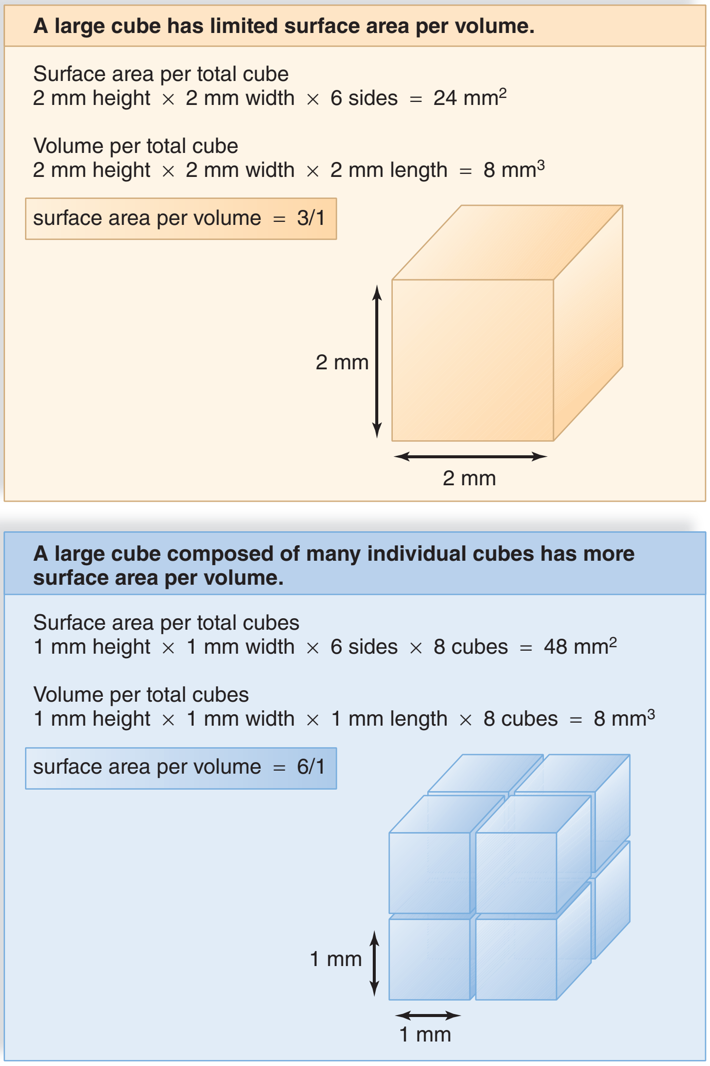
Why are cells so small? To answer this question, consider that a cell needs a surface area large enough to allow sufficient nutrients to enter and to rid itself of wastes. Small cells, not large cells, are more likely to have this adequate surface area per volume. Consider a balloon: The air in the balloon is the volume, and the balloon's skin is its surface area. A larger balloon has more volume, as you can appreciate by trying to blow up a large balloon compared to a small balloon. How might you appreciate the amount of surface area per volume? Figure 4.1D shows one way because it calculates the surface area per volume for different-sized cubes. Cutting a large cube into smaller cubes provides a lot more surface area per volume. The calculations show that a large cube has limited surface area per volume compared to a large cube composed of many individual cubes.

We would expect, then, that actively metabolizing cells would have to remain small. A chicken's egg is several centimeters in diameter, but the egg is not actively metabolizing. Once the egg is incubated and metabolic activity begins, the egg divides repeatedly without growth. Cell division restores the amount of surface area needed for adequate exchange of materials.

Further, cells that specialize in absorption have modifications that greatly increase the surface-area-to-volume ratio of the cell. The cells along the surface of the intestinal wall have surface foldings called microvilli (sing., microvillus) that increase their surface area. Nerve cells and some large plant cells are long and thin, and this increases the ratio of plasma membrane to cytoplasm. Nerve cells are shown on page 60.

▶ 4.1 CHECK YOUR PROGRESS

1. Apply the cell theory to the human body.
2. Relate a high surface-area-to-volume ratio to the efficiency of cells.



A large cube has limited surface area per volume.

Surface area per total cube
2 mm height × 2 mm width × 6 sides = 24 mm^2

Volume per total cube
2 mm height × 2 mm width × 2 mm length = 8 mm^3

surface area per volume = 3/1

A large cube composed of many individual cubes has more surface area per volume.

Surface area per total cubes
1 mm height × 1 mm width × 6 sides × 8 cubes = 48 mm^2

Volume per total cubes
1 mm height × 1 mm width × 1 mm length × 8 cubes = 8 mm^3

surface area per volume = 6/1

FIGURE 4.1D Surface-area-to-volume relationships.

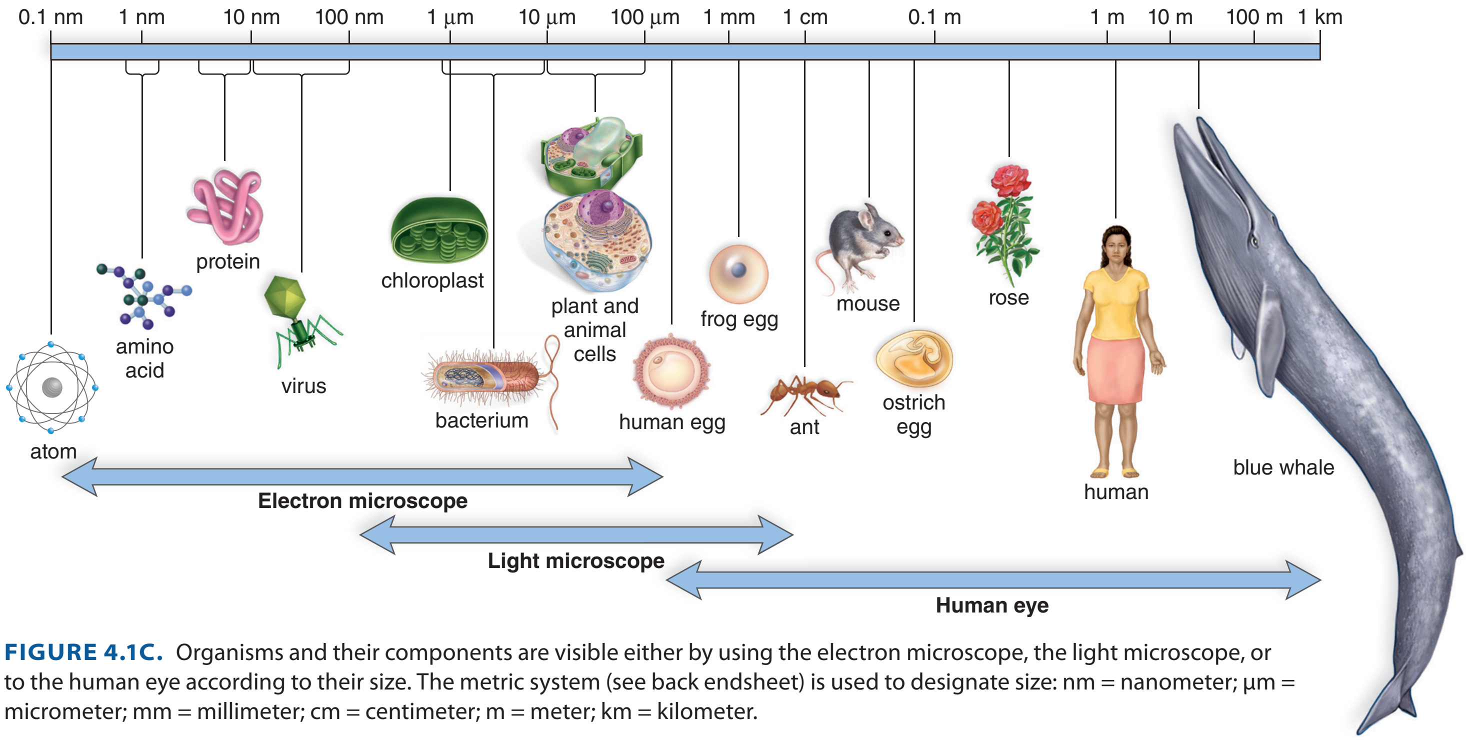


FIGURE 4.1C. Organisms and their components are visible either by using the electron microscope, the light microscope, or to the human eye according to their size. The metric system (see back endsheet) is used to designate size: nm = nanometer; µm = micrometer; mm = millimeter; cm = centimeter; m = meter; km = kilometer.

HOW SCIENCE PROGRESSES *Application*

4A Microscopes Allow Us to See Cells

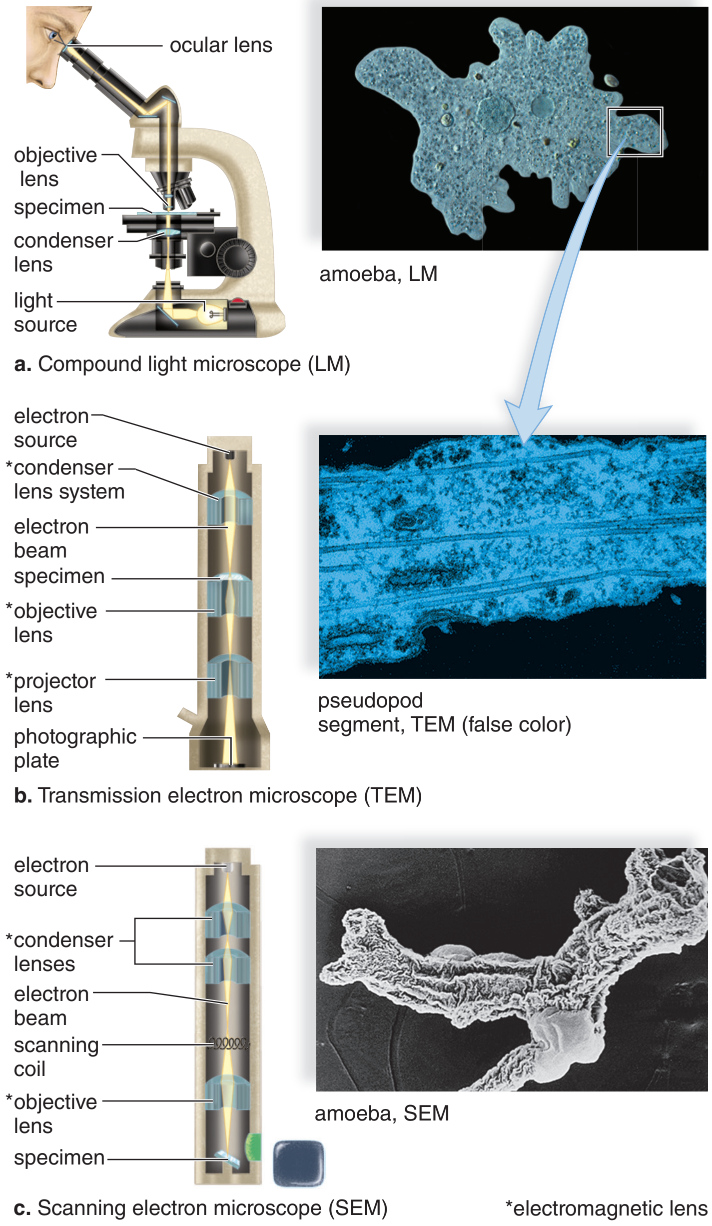
Because cells are so small, it is best to study them microscopically. A magnifying glass containing a single lens is the simplest version of a light microscope. However, such a simple device is not powerful enough to be of much use in examining cells. The **compound light microscope** is much more suitable. It has superior magnifying power because it uses a system of multiple lenses. As you can see in Figure 4A*a*, a condenser lens focuses the light into a tight beam that passes through a thin specimen (such as a unicellular amoeba, a drop of blood, or a thin slice of an organ). An objective lens magnifies an image of the specimen, and another lens, called the ocular lens, magnifies it yet again. It is the image from the ocular lens that is viewed with the eye. The most commonly used compound light microscope is called a bright-field microscope, because the specimen, which is typically stained, appears dark against a light background.

The compound light microscope is widely used in research, clinical, and teaching laboratories. However, the use of light to produce an image reduces the ability to view two objects as separate—the resolution—is not as good as with an electron microscope. The resolution limit of a compound light microscope is 0.2 µm, which means that objects less than 0.2 µm apart appear as a single object. Although there is no limit to the magnification that could be achieved with a compound light microscope, there is a definite limit to the resolution.

An electron microscope can produce finer resolution than a light microscope because, instead of using light, it fires a beam of electrons at the specimen. Electrons have a shorter wavelength than does light. The essential design of an electron microscope is similar to that of a compound light microscope, but its lenses are made of electromagnets, instead of glass. Because the human eye cannot see the images produced by electron microscopes, they are projected onto a screen or viewed on a television monitor.

There are two types of electron microscopes: the transmission electron microscope and the scanning electron microscope. These microscopes didn't become widely used until about 1970. A **transmission electron microscope** passes a beam of electrons through a specimen (Fig. 4A*b*). Because electrons do not have much penetrating ability, the section must be very thin—usually between 50 and 150 nm. The transmission electron microscope can discern fine details, with a limit of resolution around 1.0 nm and a magnifying power up to 200,000 times larger than the actual size. A **scanning electron microscope** does not pass a beam through a specimen; rather, it collects and focuses electrons that are scattered from the specimen's surface and generates an image with a distinctive three-dimensional appearance (Fig. 4A*c*).

Scientists often preserve microscopic images; these are referred to as micrographs. A captured image from a light microscope is termed a light micrograph (LM), or a photomicrograph. There are also transmission electron micrographs (TEMs) and scanning electron micrographs (SEMs). The latter two are black-and-white in their original form, but computers can colorize them for clarity.



a. Compound light microscope (LM)

b. Transmission electron microscope (TEM)

c. Scanning electron microscope (SEM)

*electromagnetic lens

FIGURE 4A Comparison of three microscopes.

CONSIDER THESE QUESTIONS

1. How would you convince a friend that what we see in micrographs actually exists?
2. TEMs are colorless but can have color added to them. Do you think color enhancement of TEMs borders on misrepresentation? Why or why not?

4.2 Prokaryotic cells evolved first

LEARNING OUTCOMES

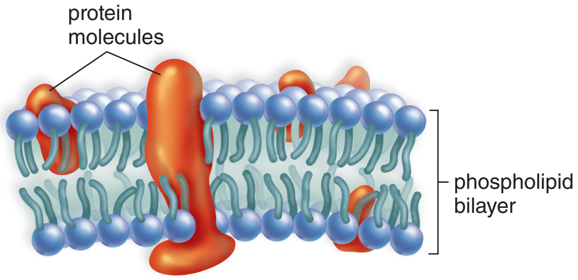
When you complete this section, you should be able to

1. Understand the classification of prokaryotes into two domains.
2. Identify and give a function for each component of a bacterium.

Fundamentally, two different types of cells exist. **Prokaryotic cells** (*pro,* before, and *karyon,* nucleus) are so named because they lack a membrane-enclosed nucleus. The other type of cell, called a eukaryotic cell, has a nucleus. Prokaryotic cells are minuscule in size compared to eukaryotic cells (Fig. 4.2A). Prokaryotes are present in great numbers in the air, in bodies of water, in the soil, and also in and on other organisms.

As discussed on page 14, prokaryotic cells are divided into two groups, largely based on biochemical, including DNA, evidence. These two groups are so biochemically different that they have been placed in separate domains, called domain **Bacteria** and domain **Archaea.**

Figure 4.2B shows the generalized structure of a bacterium. Like a eukaryotic cell, a bacterium is full of a semifluid substance called **cytoplasm** that is enclosed by a **plasma membrane.** The plasma membrane is a phospholipid bilayer (see Fig. 3.6) with embedded proteins:



The plasma membrane has the important function of regulating the entrance and exit of substances into and out of the cytoplasm. After all, the cytoplasm has a normal composition that needs to be maintained. It contains thousands of **ribosomes** where proteins are produced. A long, looped, threadlike strand of DNA, the **chromosome** of a prokaryotic cell, is located within a region of the cytoplasm known as a **nucleoid.** When bacteria reproduce by splitting in two, each new cell gets a copy of the chromosome. Cyanobacteria (*cyan*, blue-green) are able to photosynthesize in the same manner as plants because they have light-absorbing chlorophyll on internal membranes.

In addition to the plasma membrane, bacteria have a **cell wall,** which helps maintain the shape of the cell. The cell wall may in turn be surrounded by a **capsule.** Many short, hollow protein rods called **pili** project through the cell wall. Pili attach the cell to solid substances and produce a slime that coats your teeth, rocks at the bottom of lakes, and the hulls of ships, for example. Motile bacteria usually have long, very thin flagella (sing., flagellum), which rotate like propellers, rapidly moving the bacterium in a fluid medium.

Bacteria are well known for causing serious diseases, such as tuberculosis, anthrax, tetanus, throat infections, and gonorrhea. However, they are important to the environment because they decompose the remains of dead organisms and contribute to the cycling of chemicals in ecosystems. Also, their great ability to synthesize molecules can be put to use for the manufacture of all sorts of products, from industrial chemicals to foodstuffs and drugs.

Video
E. Coli Wars

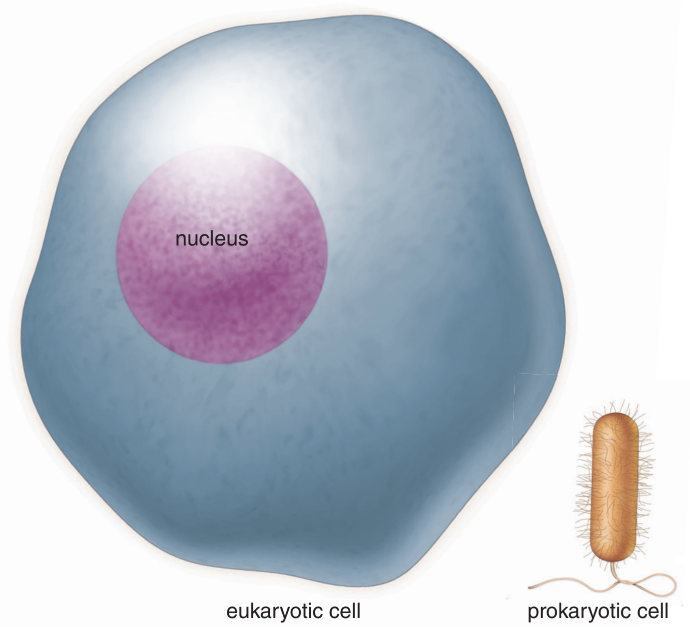


FIGURE 4.2A Eukaryotic cells are much larger than prokaryotic cells, as shown in this proportional drawing.

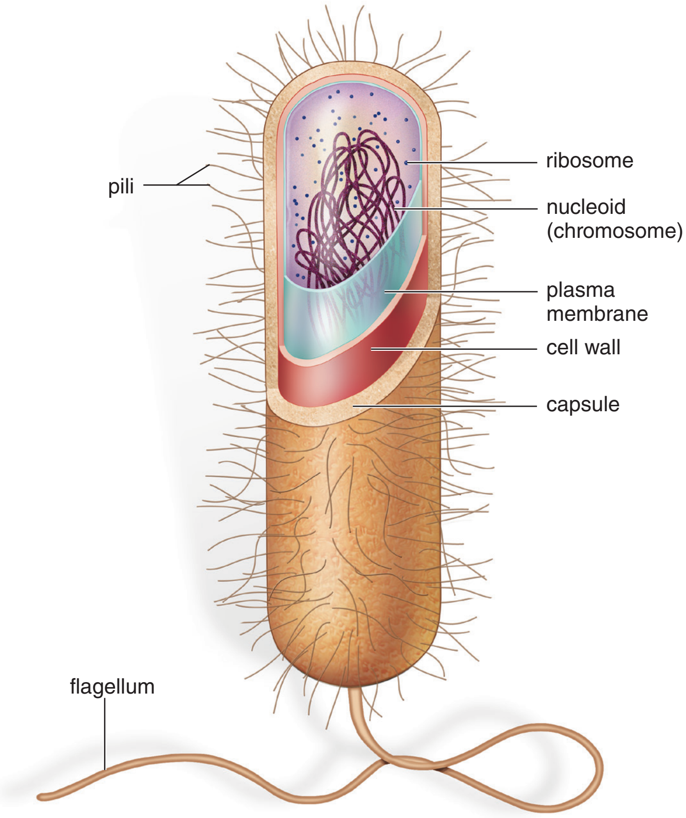


FIGURE 4.2B A prokaryotic cell such as this bacterium is structurally simple but metabolically complex.

▶ **4.2 CHECK YOUR PROGRESS**

1. Explain the classification of prokaryotes into two domains.
2. Identify a function for each labeled structure in Figure 4.2B.

4.3 Eukaryotic cells contain specialized organelles: An overview

LEARNING OUTCOMES

When you complete this section, you should be able to

1. Recognize the benefits of eukaryotic cells having organelles.
2. Associate particular organelles with animal and plant cells.

Eukaryotic cells (*eu,* true, and *karyon,* nucleus) have a membrane-enclosed **nucleus,** which houses their DNA. As depicted in Figure 1.8D, protists, fungi, plants, and animals are the groups of organisms that have eukaryotic cells and are in the domain **Eukarya,** the third domain of life.

Eukaryotic cells are much larger than prokaryotic cells, and therefore they have less surface area per volume than prokaryotic cells (see Fig. 4.1D). This disadvantage has been solved because the cells are compartmentalized—they have compartments. Just like a house that has separate rooms, the compartments of a eukaryotic cell are specialized for particular functions. In the kitchen of a house are utensils, appliances, and counters necessary for preparing and serving meals, while a bedroom contains personal effects and furniture for sleeping and storing clothes. Similarly, a cell contains **organelles** (meaning "little organs") that are specialized and perform only specific functions. The organelles are located within the cytoplasm, a semifluid interior enclosed by a plasma membrane. As in prokaryotic cells, the plasma membrane is a phospholipid bilayer that contains proteins, shown in the circular blowup of Figure 4.3A.

MP3 Organelles

Eukaryotic cells are rich in membrane, and most organelles are membranous. Originally, the term organelle referred only to membranous structures, but we will use it to include any well-defined subcellular structure. By that definition, the little particles called ribosomes are also organelles. At first it might seem difficult to learn the names and functions of all the structures in plant and animal cells. One technique that will help is to have a mental image of the structure and then discover its function. So in Figures 4.3A and 4.3B, first look at the structure and then follow the leader back to its name and function. A well-known truism in biology states, "Structure suits function." Why might that be? In the course of evolution, those organisms whose cells possessed organelles

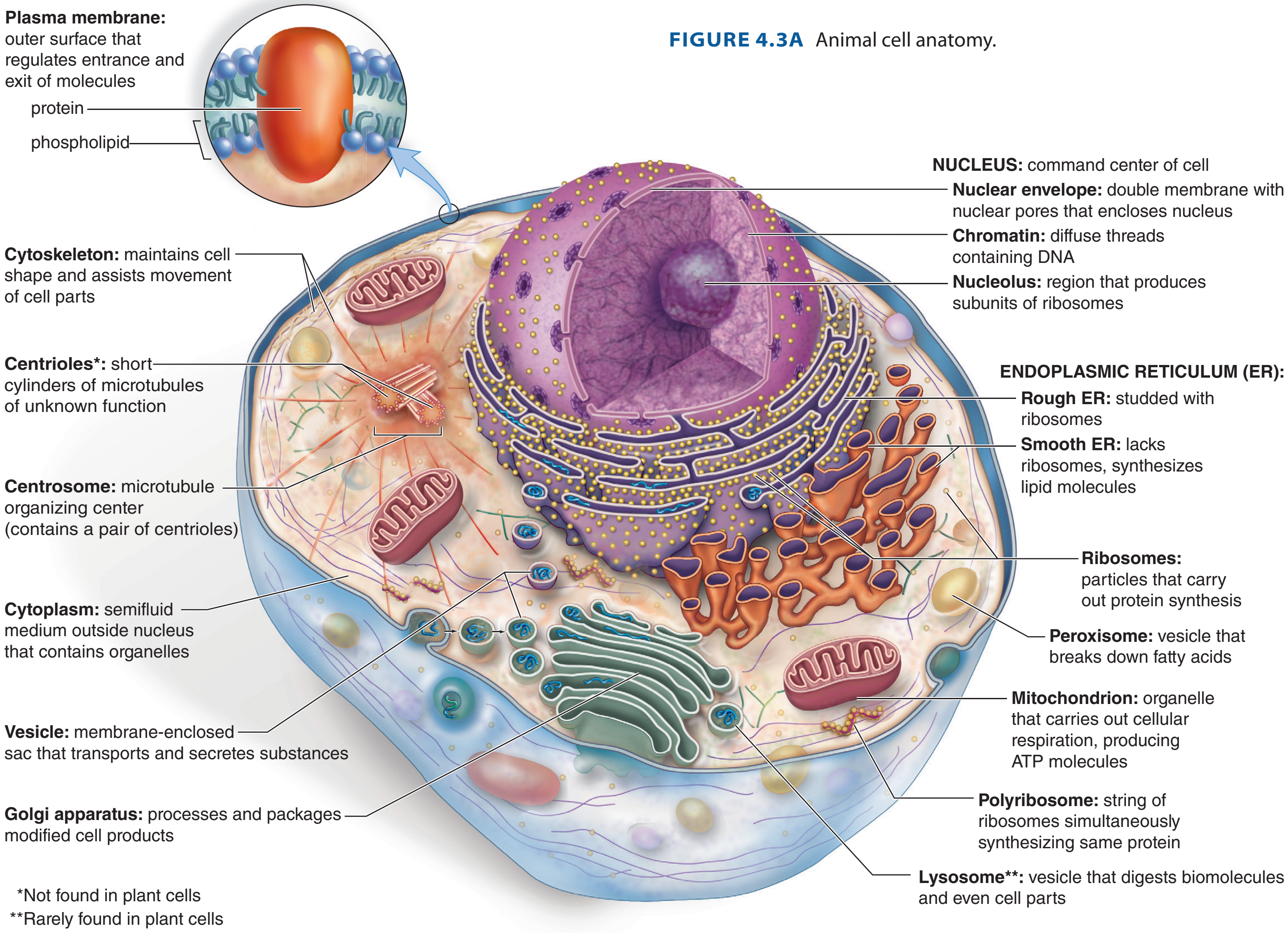


FIGURE 4.3A Animal cell anatomy.

*Not found in plant cells
**Rarely found in plant cells

suited to their function were more likely to have surviving offspring, and slowly over time all organisms of that group had such cells and organelles.

In this chapter we are going to concentrate on aspects of structure and function common to both animal and plant cells. Both types of cells have a nucleus that houses chromatin (DNA) and ribosomes that produce proteins in the same manner, for example. The fundamental aspects of cellular organization and function do not vary between the two types of cells. Still, we have an opportunity in this chapter to point out how the two types of cells differ as listed in Table 4.3. The cell wall of plants is covered in Chapter 5, which concerns the structure and function of cell surfaces. However, Table 4.3 will assist you in learning the major differences between animal and plant cells. The other cell structures (plasma membrane, nucleus, centrosome, endoplasmic reticulum, ribosomes, Golgi, peroxisomes, cytoskeleton) are present in both plant and animal cells.

The various cells in your body have the structures depicted in Figure 4.3A but many of your cells have additional structures and modifications to carry on particular functions. Similarly, the plants in your garden and the trees in your yard have cells with the structures shown in Figure 4.3B but they also have cells that are specialized in different ways. Multicellular organisms in particular have specialized cells and this leads to their diversity in form and capabilities.

TABLE 4.3 Animal and Plant Cell Differences

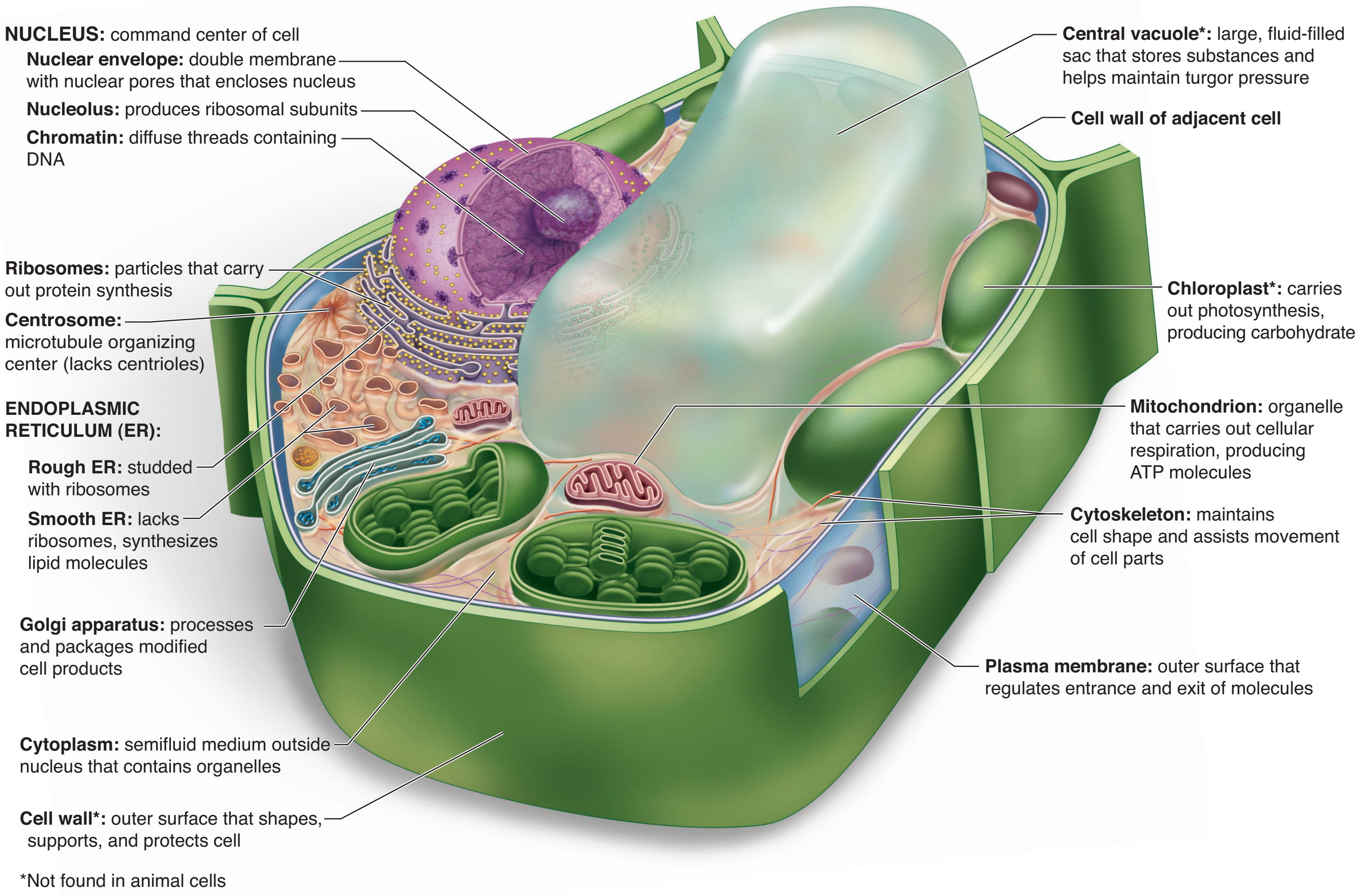
Structure	Animal Cell	Plant Cell
Cell wall	No	Yes
Chloroplast	No	Yes
Lysosomes	Yes	Rarely present
Centrioles	Yes	No
Large central vacuole	No	Yes
Shape	Round	Rectangular

It's good to keep in mind as you study cell structures and their functions that despite their small size cells display all the characteristics of life we studied in Chapter 1. This chapter tells you how they can accomplish this feat.

4.3 CHECK YOUR PROGRESS

1. Identify how a large eukaryotic cell benefits from having organelles.
2. Explain why you would expect plant cells to have chloroplasts and both plant and animal cells to have mitochondria.

FIGURE 4.3B Plant cell anatomy.



The Nucleus and the Endomembrane System

This part of the chapter discusses certain organelles of eukaryotic cells—namely, the nucleus, the ribosomes, the endoplasmic reticulum, and the Golgi apparatus, which are all involved in producing proteins that may serve necessary functions in the cell or may be secreted out of the cell.

4.4 The nucleus is a control center

LEARNING OUTCOMES

When you complete this section, you should be able to

1. Identify and give a function for each component of the nucleus.
2. Determine how the nucleus controls the functioning of the ribosomes.

The nucleus is a prominent structure in a eukaryotic cell (Fig. 4.4A). It generally has an oval shape and is located near the center of a cell. The nucleus contains DNA, the genetic material that is passed from cell to cell and from generation to generation. DNA dictates which proteins a cell is to synthesize and these proteins determine the cell's structure and functions; therefore, the nucleus is the command center of a cell.

At the time of cell division, DNA and proteins are organized into the several **chromosomes** of a eukaryotic cell. Following cell division, the chromosomes become extended into **chromatin,** which looks grainy, but actually is a network of fine strands. A **nucleolus** is a dark region of chromatin where the subunits of ribosomes are produced.

The nucleus is separated from the cytoplasm by a double membrane known as the **nuclear envelope.** Even so, the nucleus communicates with the cytoplasm. The nuclear envelope has **nuclear pores** of sufficient size to permit the passage of ribosomal subunits out of the nucleus into the cytoplasm, and the passage of proteins from the cytoplasm into the nucleus. High-power electron micrographs show nonmembranous components associated with the pores that form a nuclear pore complex.

The nuclear envelope is a part of an **endomembrane system,** which is composed of membranous structures that are either directly connected or communicate by way of transport vesicles.

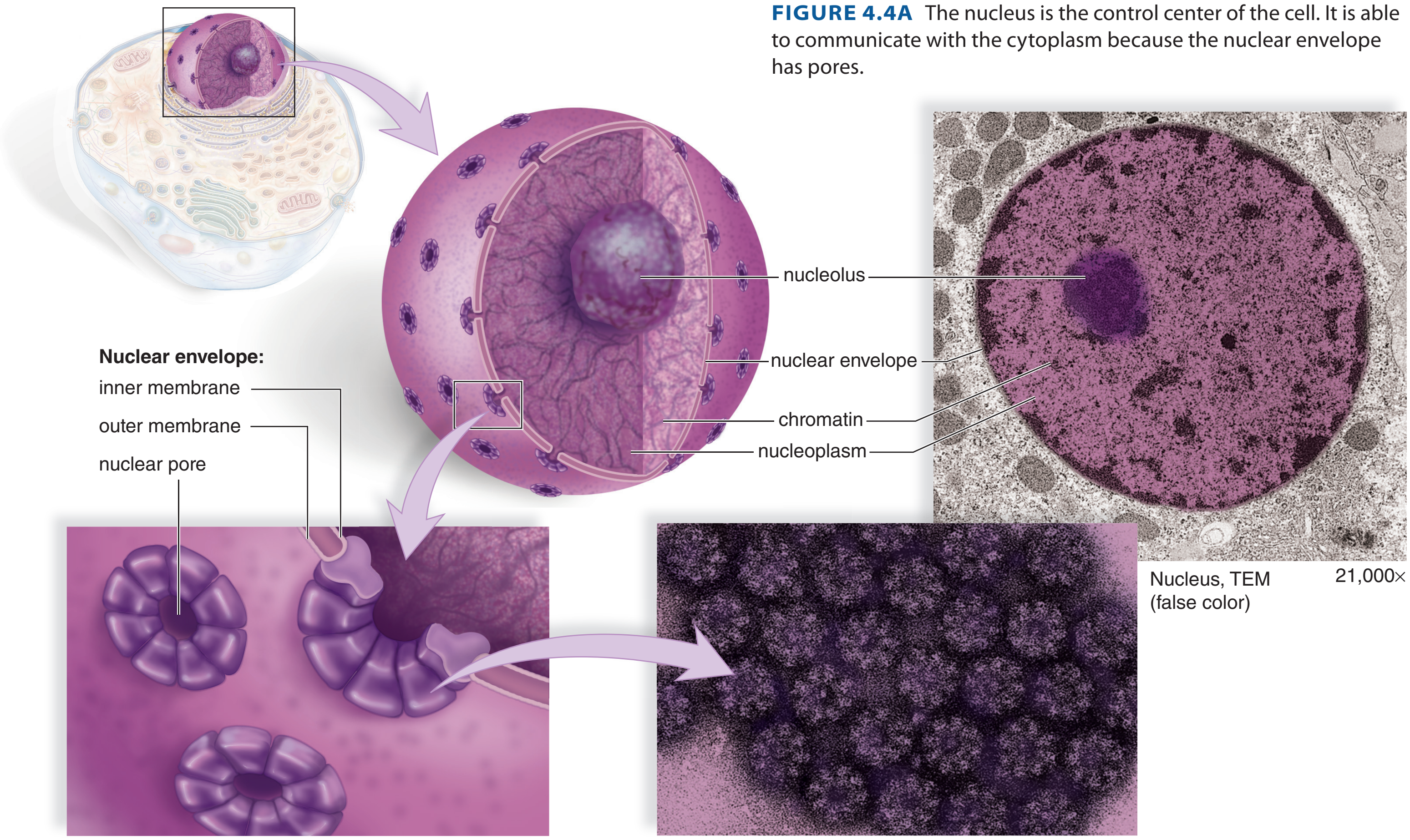


FIGURE 4.4A The nucleus is the control center of the cell. It is able to communicate with the cytoplasm because the nuclear envelope has pores.

Nuclear pores, drawing

Nuclear pores, TEM (false color)

Ribosomes Ribosomes are particles that produce plentiful proteins. When you are going to make something, you usually need a surface on which to do your work. In the same manner, a cell uses ribosomes as a workbench for producing proteins.

Ribosomes are measured in nanometers, which means they are quite small; eukaryotic ribosomes are slightly larger than those in prokaryotes. In both types of cells, ribosomes are composed of two subunits, one large and one small.

In eukaryotic cells, some ribosomes occur freely within the cytoplasm, either singly or in groups called polyribosomes. Other ribosomes attach to the **endoplasmic reticulum** (**ER**), a membranous system of flattened saccules (small sacs) and tubules that is contiguous with the nuclear envelope (Fig. 4.4B, *left*).

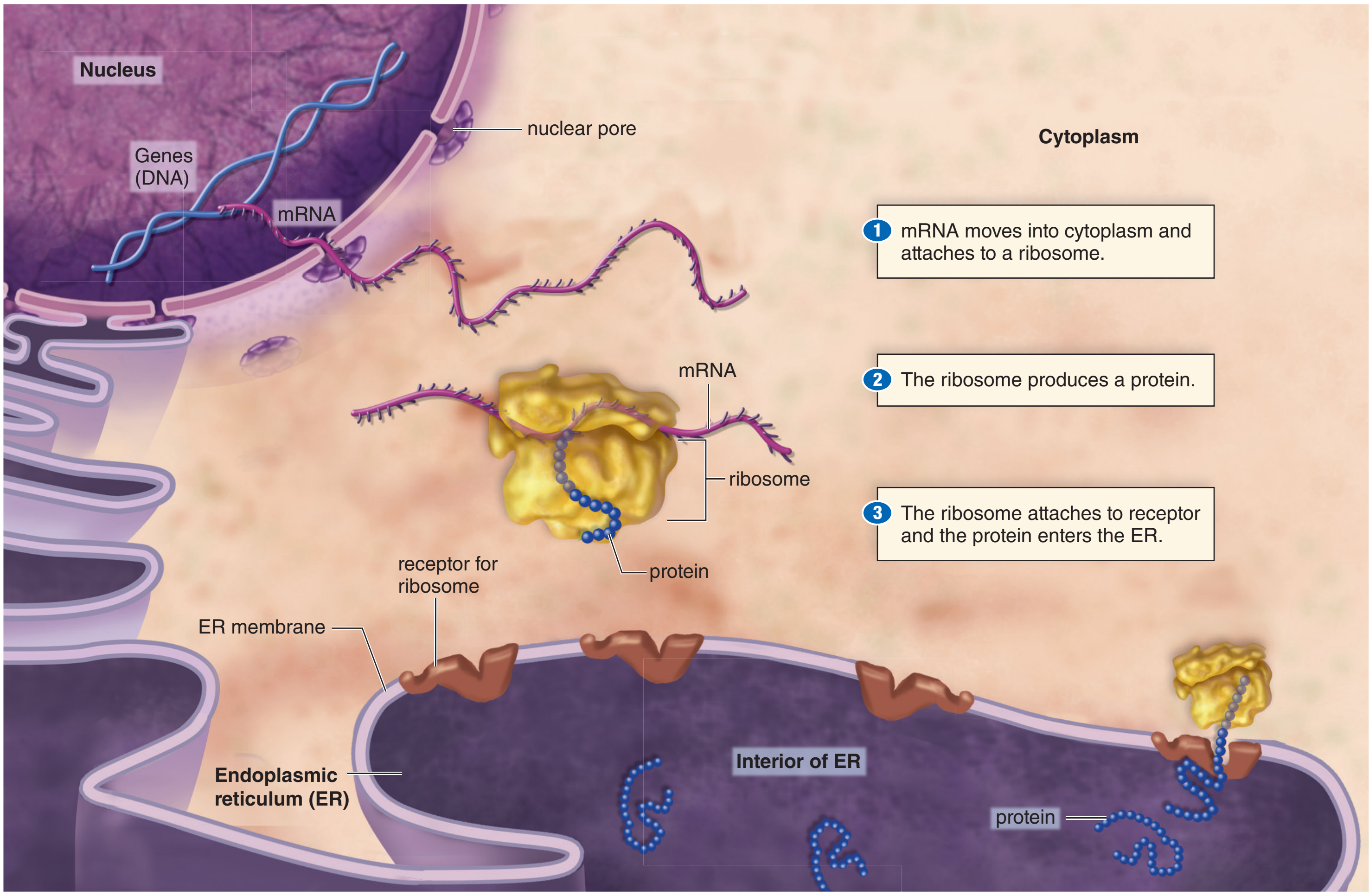
The nucleus is the control center of the cell because the genes specify the sequence of amino acids in proteins. When a protein is needed, an RNA copy of a gene called messenger RNA (mRNA) leaves the nucleus by way of a nuclear pore and becomes attached to a ribosome. A ribosome uses the sequence of nucleotides in the mRNA as a code to produce a protein with the correct order of its amino acids (see page 200). Just as a dressmaker uses a pattern and directions to make a garment, so a ribosome uses the coded information provided by mRNA to produce a particular protein.

Attachment of Ribosomes to the ER Proteins produced by cytoplasmic ribosomes often enter a membranous organelle. Those produced by ribosomes attached to the ER end up in the interior of the ER. As shown in Figure 4.4B, *right*, ① after the mRNA leaves the nucleus and enters the cytoplasm, ② it becomes attached to a ribosome, and ③ the ribosome becomes attached to the ER. The newly produced protein enters the interior of the ER. The protein folds into the correct shape inside the ER. Recall from Figure 3.8 that a protein can have up to four levels of organization. The shape of a protein is very important to its functioning appropriately.

▶ 4.4 CHECK YOUR PROGRESS

1. How does the nuclear envelope permit RNA to exit the nucleus?
2. Identify the relationship between ribosomes and the nucleus and also the ER.

FIGURE 4.4B mRNA is formed in the nucleus of a gene and moves to cytoplasm where protein synthesis occurs at a ribosome. Attachment of ribosome to endoplasmic reticulum (ER) makes it rough ER.



4.5 The ER produces and transports proteins and lipids to the Golgi apparatus

LEARNING OUTCOMES

When you complete this section, you should be able to

1. Identify how the ER and the Golgi apparatus work together to produce and export a molecular product.
2. Explain the function of lysosomes in cells.

The term endoplasmic reticulum is a difficult one but becomes simpler if we break it down. *Endoplasmic* means "within the plasm" of the cell and *reticulum* is an elegant way of saying "network." Just as a long street can be lined by different neighborhoods and have different names according to the neighborhood, the outer membrane of nuclear envelope becomes the membrane of the ER. The membranous tubules and flattened sacs of the ER typically account for more than half of the total membrane within an average animal cell. Its twists and turns as it courses through the cytoplasm like a long snake enclose a single internal space. This space will be termed the interior of the ER (Fig. 4.4B). If you compare Figure 4.4B to Figure 4.5A, you can see that Figure 4.4B shows only a small portion of the ER found in a cell.

Because many ribosomes attach themselves to the ER, it becomes the location where all the proteins are produced for the many membranes inside a eukaryotic cell as well as most of the proteins that are secreted from the cell. In humans, the protein insulin is secreted by the pancreas into the blood and then circulates about the body. Aside from proteins, the ER also produces various lipids.

Types of ER The ER is divided into the rough ER and the smooth ER. Only the **rough ER** (**RER**) is studded with ribosomes. The ribosomes are attached to the side of the membrane that faces the cytoplasm. Figure 4.4B shows how a protein enters the interior of the ER from an attached ribosome. Once inside, a protein undergoes the process of folding into its final shape.

Smooth ER (**SER**), which is continuous with rough ER, does not have attached ribosomes. Therefore, it has a smooth appearance in electron micrographs and more important it does not participate in protein production. Smooth ER is abundant in gland cells, where it synthesizes lipids of various types. For example, cells that synthesize steroid hormones from cholesterol have much SER. In the liver, SER, among other functions, adds lipid to proteins, forming the lipoproteins that carry cholesterol in the blood. Also, the SER of the liver increases in quantity when a person consumes alcohol or takes barbiturates on a regular basis, because SER contains the enzymes that detoxify these molecules.

The RER and SER, working together, produce membrane, which is composed of phospholipids and various types of proteins including those that have carbohydrate chains (see Fig. 5.1A). Proteins to be secreted from the cell remain in the interior of the ER, but the ones destined to become membrane constituents become embedded in its membrane. Because the ER produces membrane, it can form the transport vesicles by which it communicates with the Golgi apparatus. **Transport vesicles** pinch off from the ER and carry protein and lipids, notably to the Golgi apparatus, where they undergo further modification. The products of the Golgi apparatus are utilized by the cell or repackaged in secretory vesicles that make their way to the plasma membrane where they are secreted (see Fig. 4.5B).

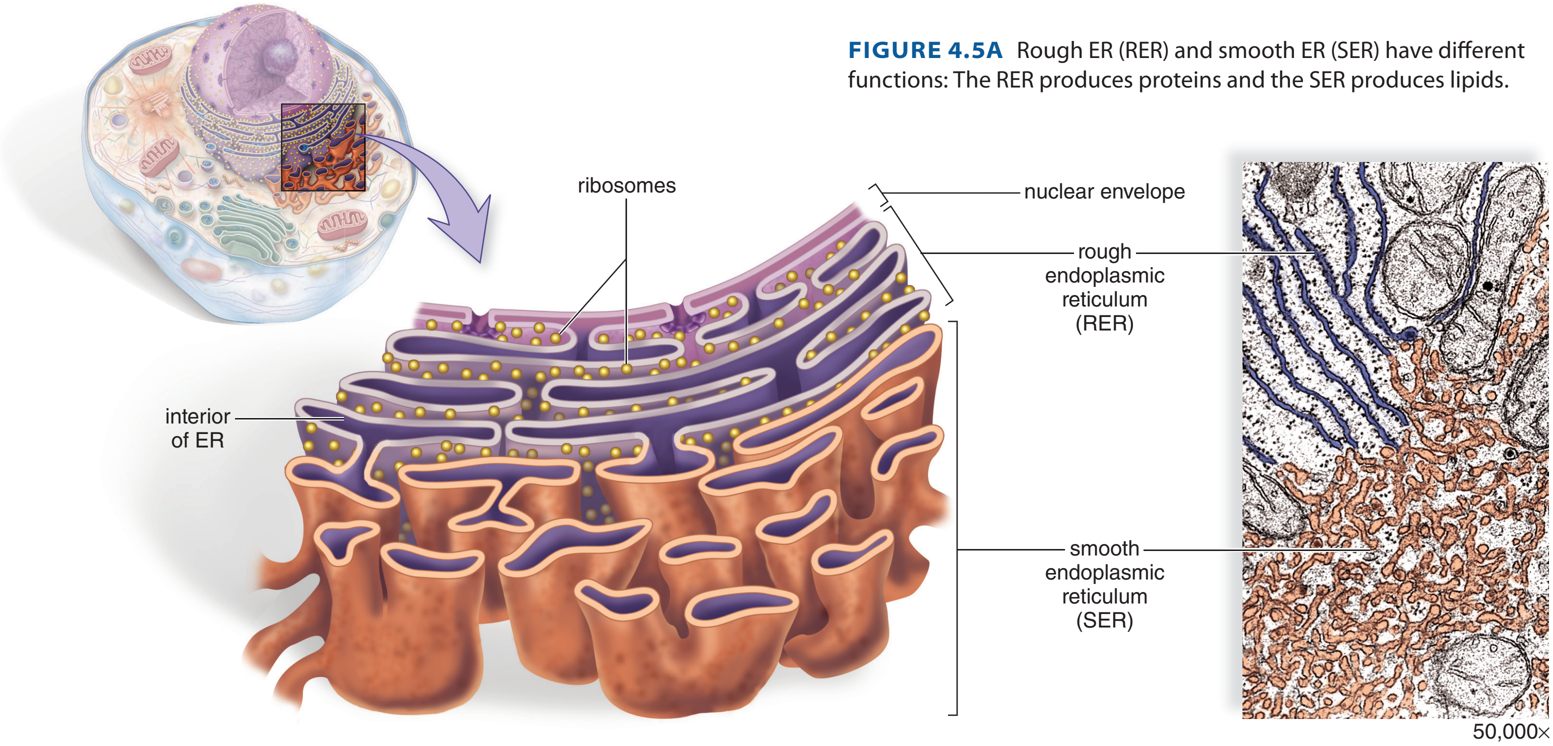


FIGURE 4.5A Rough ER (RER) and smooth ER (SER) have different functions: The RER produces proteins and the SER produces lipids.

Golgi Apparatus The **Golgi apparatus** is named for Camillo Golgi, who discovered its presence in cells in 1898. The Golgi apparatus, or simply the Golgi, typically consists of a stack of three to twenty slightly curved, flattened saccules whose appearance can be compared to a stack of pancakes (Fig. 4.5B). One side of the stack is directed toward the ER, and the other side is directed toward the plasma membrane. Vesicles can frequently be seen at the edges of the saccules.

The Golgi receives, processes, and packages proteins and lipids, so that they may be sent to their final destination in the cell. In particular, it readies proteins for secretion. Protein-filled vesicles that bud from the rough ER and lipid-filled vesicles that bud from the smooth ER are received by the Golgi. Thereafter, the Golgi alters these substances as they move through its saccules. For example, proteins may have attached carbohydrate chains and the Golgi contains enzymes that modify these chains. In some cases, the modified carbohydrate chain serves as a signal molecule that determines the protein's final destination in the cell.

The Golgi sorts and packages proteins and lipids in vesicles that carry them to their final destination. Secretory vesicles proceed to the plasma membrane, where they stay until a signal molecule triggers the cell to release them. Then their membrane becomes part of the plasma membrane as they discharge their contents during **secretion.** Digestive enzymes, for example, are secreted into a tube that carries them to the digestive tract, where they break down food to nutrients molecules.

Lysosomes are another type of vesicle produced by the Golgi apparatus. They have a very low internal pH and contain powerful hydrolytic digestive enzymes. Lysosomes have significant digestive functions inside the cell. For example, they are important in recycling cellular material and digesting worn-out organelles, such as old mitochondria (Fig. 4.5C).

Sometimes biomolecules are engulfed (brought into a cell by vesicle formation) at the plasma membrane. When a lysosome fuses with such a vesicle, its contents are digested by lysosomal enzymes into simpler subunits that then enter the cytoplasm. Some white blood cells defend the body by engulfing bacteria, which are then enclosed within vesicles. When lysosomes fuse with these vesicles, the bacteria are digested.

A cell can have dozens of lysosomes and this perhaps suggests their importance in helping to maintain homeostasis inside a cell. Unfortunately there are many different types of lysosomal storage diseases, so called because a molecule builds up in a lysosome because the enzyme needed to break it down is absent or nonfunctional. Tay-Sachs disease is one such condition, in which a newborn appears healthy but then gradually becomes nonresponsive, deaf, and blind before dying within a few months. The brain cells are filled with particles containing a type of lipid that cannot be digested by lysosomes.

Animation
Lysosomes

4.5 CHECK YOUR PROGRESS

1. Identify the path of a protein from production to secretion from a cell.
2. Contrast the roles of lysosomes and secretory vesicles in cells and suggest a possible way the Golgi is able to produce both types of vesicles.

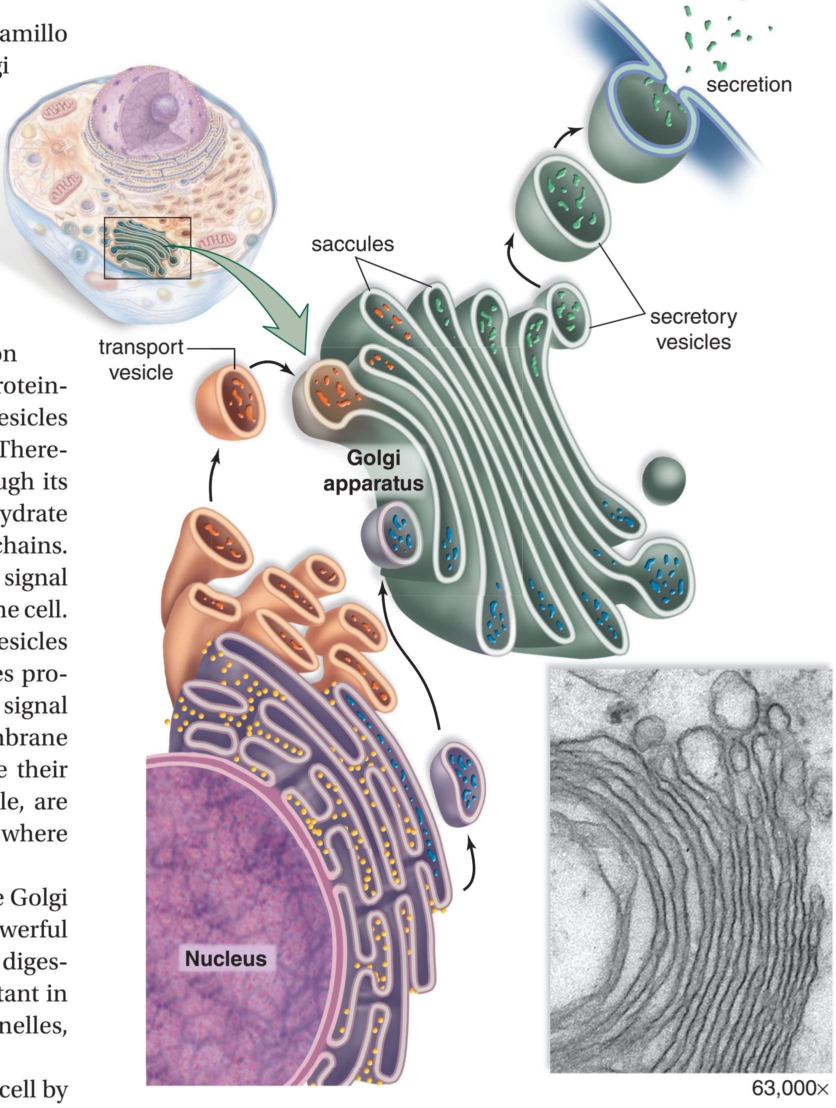


FIGURE 4.5B The Golgi apparatus receives molecules for modification in vesicles from both rough and smooth ER. After processing these molecules, it packages them for secretion at the plasma membrane.

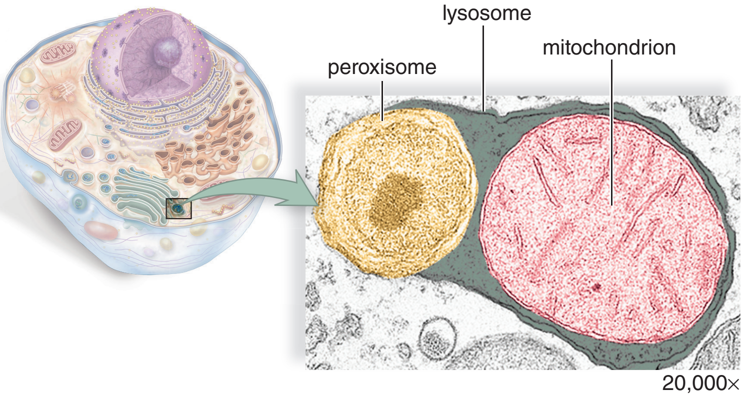


FIGURE 4.5C Lysosomes fuse with incoming vesicles and digest their contents. They also take in and destroy spent organelles, as shown here.

HOW SCIENCE PROGRESSES *Application*

4B Pulse-Labeling Allows Observation of the Secretory Pathway

The pathway of protein secretion was observed by George Palade and his associates using a pulse-chase technique. The rough ER was *pulse-labeled* by letting cells metabolize for a very short time with radioactive amino acids. Then the cells were given an excess of nonradioactive amino acids. This *chased* the labeled amino acids out of the ER into transport vesicles.

Electron microscopy techniques allowed these researchers to trace the fate of the labeled amino acids, as shown in Figure 4B: ① The labeled amino acids were found in the ER, then in ② transport vesicles, and then in ③ the Golgi apparatus, before appearing in ④ vesicles at the plasma membrane and finally being released.

CONSIDER THESE QUESTIONS

1. Why would Palade have labeled sulfur and not carbon in the amino acids? (See Fig. 3.7A.)
2. Where else might Palade have found the labeled amino acids in the cell? (See Fig. 4.4B.)

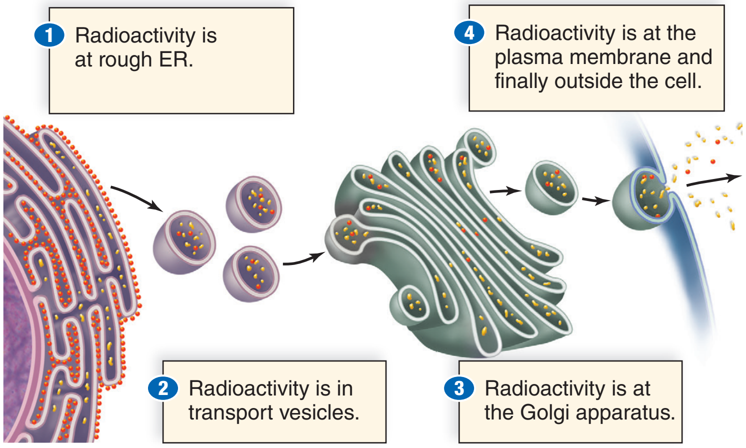


FIGURE 4B The secretory pathway.

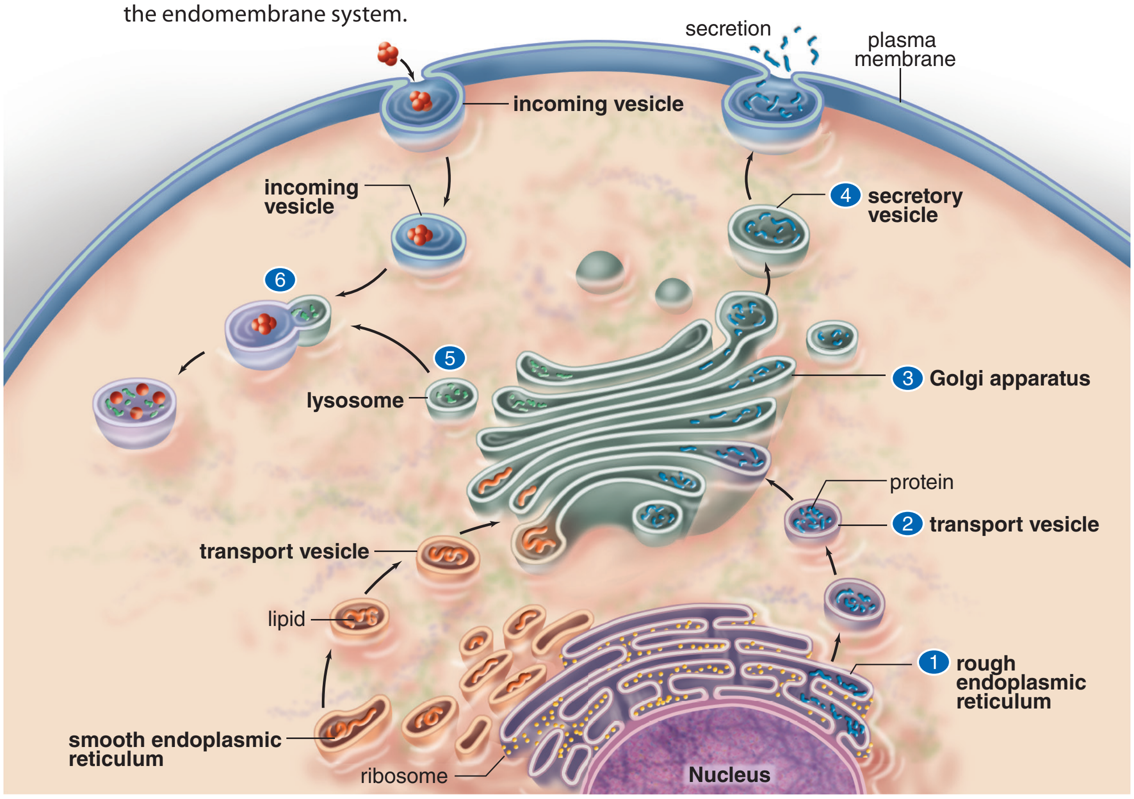
4.6 The organelles of the endomembrane system work together

LEARNING OUTCOME

When you complete this section, you should be able to

1. Describe the structure and function of the organelles that belong to the endomembrane system.

FIGURE 4.6 The organelles of the endomembrane system.



The **endomembrane system** includes the nuclear envelope, the endoplasmic reticulum (ER), the Golgi apparatus, lysosomes, and the transport vesicles.

Figure 4.6 shows how the components of the endomembrane system work together: ① In the secretory pathway, proteins produced in the rough ER are carried in ② transport vesicles to ③ the Golgi apparatus, which sorts the proteins and packages them into vesicles that transport them to various cellular destinations.

④ Secretory vesicles take the proteins to the plasma membrane, where they exit the cell when the vesicles fuse with the membrane. For example, secretion into ducts occurs when the salivary glands produce saliva or when the pancreas produces digestive enzymes. Similarly, lipids move from the smooth ER to the Golgi apparatus and can eventually be secreted.

⑤ In animal cells, a lysosomal pathway occurs. Lysosomes produced by the Golgi apparatus ⑥ fuse with incoming vesicles from the plasma membrane and digest biomolecules and debris. White blood cells are well known for engulfing pathogens (e.g., disease-causing viruses and bacteria) that are then broken down in lysosomes.

4.6 CHECK YOUR PROGRESS

1. Identify which organelles in the endomembrane system produce, modify, or break down a biomolecule.

Vacuoles and Vesicles

Cells have various membranous sacs that look the same in electron micrographs but have different functions. Lysosomes, as discussed previously, contain powerful hydrolytic enzymes that digest biomolecules and even cell parts. Peroxisomes are more specialized and assist mitochondria by breaking down lipids, among other functions. Some of the vacuoles in protists and plants are unique to them and not found in other eukaryotes.

4.7 Vacuoles are common in plant cells

LEARNING OUTCOME

When you complete this section, you should be able to

1. Contrast the function of vacuoles in protists with their function in plants.

Like vesicles, **vacuoles** are membranous sacs, but vacuoles are larger than vesicles. The vacuoles of some protists are quite specialized, including contractile vacuoles for ridding the cell of excess water and digestive vacuoles for breaking down nutrients. Vacuoles usually store substances. Few animal cells contain vacuoles, but fat cells contain a very large lipid-engorged vacuole that takes up nearly two-thirds of the volume of the cell!

Plant vacuoles contain not only water, sugars, and salts but also water-soluble pigments and toxic molecules. The pigments are responsible for many of the red, blue, or purple colors of flowers and some leaves. The toxic substances help protect a land plant from feeding insects.

Typically, plant cells have a large **central vacuole** that may take up to 90% of the volume of the cell. The vacuole is filled with a watery fluid called cell sap that gives added support to the cell (Fig. 4.7). **Turgor pressure,** which is the pressure of cell contents against the plant cell wall, is maintained by the central vacuole. A plant cell can rapidly increase in size by enlarging its vacuole. Eventually, a plant cell also produces more cytoplasm.

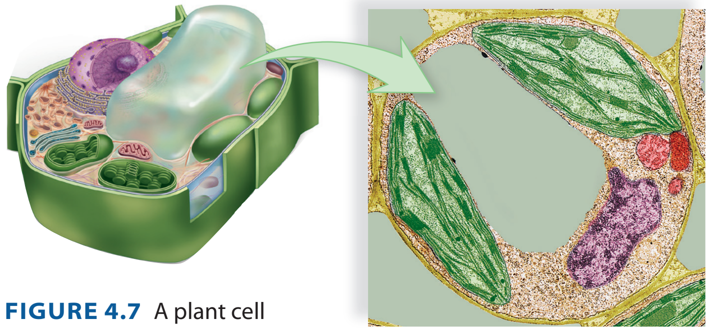


FIGURE 4.7 A plant cell vacuole supports and fills the cell.

7,700×

The central vacuole functions in storage of both nutrients and wastes. Metabolic waste products are pumped across the vacuole membrane and stored permanently in the central vacuole. As organelles age and become nonfunctional, they fuse with the vacuole, where digestive enzymes break them down. This is a function carried out by lysosomes in animal cells.

4.7 CHECK YOUR PROGRESS

1. Explain why the central vacuole of plants is more than a bag of water.

4.8 Peroxisomes have many different functions

LEARNING OUTCOME

When you complete this section, you should be able to

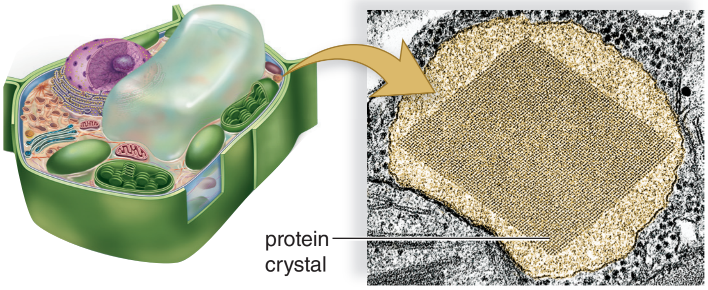
1. Discuss in general the functions of peroxisomes.

Peroxisomes, similar to lysosomes, are membrane-enclosed vesicles that contain enzymes. A concentration of enzymes resulting in a protein crystal is characteristic of peroxisomes (Fig. 4.8). Peroxisomes originate at the ER and thereafter they import enzymes from the cytoplasm. Some of these enzymes synthesize needed substances and several of them break down toxic substances. All peroxisomes contain enzymes whose actions result in hydrogen peroxide (H_2O_2):

$$RH_2 + O_2 \qquad R + H_2O_2$$

Hydrogen peroxide, a toxic molecule, is immediately broken down to water and oxygen by another peroxisomal enzyme called catalase. When hydrogen peroxide is applied to a wound, bubbling occurs as catalase breaks it down.

Peroxisomes have varied functions but are especially prevalent in cells that are synthesizing and breaking down lipids. In the liver, some peroxisomes produce bile salts from cholesterol, and others break down fats. In a 1992 movie, *Lorenzo's Oil,* the peroxisomes in a boy's cells lack a membrane protein needed to import a specific enzyme and/or long-chain fatty acids from the cytoplasm. As a result, long-chain fatty acids accumulate in his brain, and he suffers neurological damage. This disorder is known as adrenoleukodystrophy.



155,000×

FIGURE 4.8 Peroxisomes contain so many enzymes, they sometimes form a protein crystal.

Plant cells also have peroxisomes. In germinating seeds, they oxidize fatty acids into molecules that can be converted to sugars needed by the growing plant. In leaves, peroxisomes can assist photosynthesis.

4.8 CHECK YOUR PROGRESS

1. Identify a function that would immediately distinguish peroxisomes from lysosomes.

Chloroplasts and Mitochondria

Chloroplasts transform solar energy into the energy of carbohydrates, which serve as organic food for themselves and all organisms in the biosphere. Mitochondria transform the energy of carbohydrates to that of ATP molecules. All cells use ATP molecules as a source of energy for metabolic reactions and processes.

4.9 Chloroplasts and mitochondria have opposite functions

LEARNING OUTCOME

When you complete this section, you should be able to

1. Contrast the structure and function of chloroplasts with that of mitochondria.

We learned in Chapter 1 that all organisms must acquire energy and nutrients from their environment. Plants, however, can use solar energy and the inorganic nutrients water and carbon dioxide to make energy-rich carbohydrates during a process called **photosynthesis.** Carbohydrates serve as organic food for plants; therefore, we say that plants make their own food. Photosynthesis not only takes in carbon dioxide but also releases oxygen.

Plants can photosynthesize because their cells contain organelles called **chloroplasts.** Each plant cell may contain as many as 100 chloroplasts, and a square millimeter of leaf can contain up to 500,000 chloroplasts (Fig. 4.9). The green pigment chlorophyll, and other pigments as well, are responsible for the ability of chloroplasts to absorb solar energy. Within a chloroplast, chlorophyll is located in the membrane of flattened sacs called thylakoids.

Chloroplasts are of great significance to the biosphere, including humans, because they are the ultimate source of all food for organisms. Consider that you either feed directly on plants or on animals that have fed on plants. Another source of food for the biosphere is carbohydrates made by cyanobacteria and algae, because they also use pigments to absorb solar energy and photosynthesize in the same manner as plants.

How would you know that chloroplasts produce carbohydrates when the sun is shining? One way is to look for starch grains to accumulate in plant cells when the sun is out. Set a plant in the dark and the starch grains disappear.

In contrast to chloroplasts, nearly all organisms and types of cells, including both plant and animal cells, contain mitochondria (Fig. 4.9). **Mitochondria** are indispensable to cells because they carry on **cellular respiration,** the process that transforms the energy of carbohydrates to that of ATP molecules. It's called cellular respiration because mitochondria take in oxygen and give off carbon dioxide. Because mitochondria produce ATP, they are called the powerhouse of a cell.

Cellular respiration and photosynthesis are opposite reactions:

$$\text{carbohydrate} + \text{oxygen} \leftrightarrows \text{carbon dioxide} + \text{water} + \text{energy}$$

For cellular respiration, read left to right and replace energy with ATP. For photosynthesis, read right to left and replace energy with solar energy.

Cells use ATP, not glucose, as a direct source of metabolic energy—using a molecule of glucose would be energy-inefficient and wasteful. You use change, not a dollar bill, to buy something that costs five cents. In the same manner, an organism converts

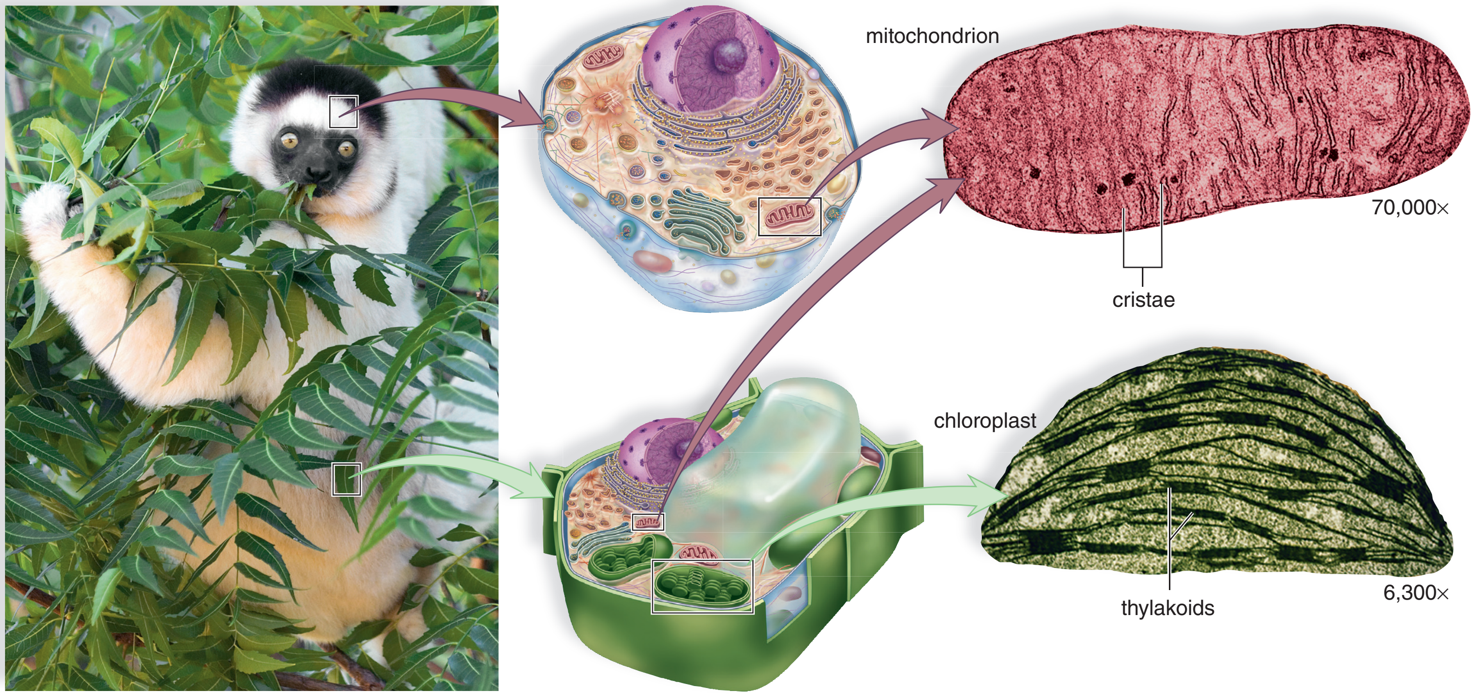


FIGURE 4.9 Plant cells carry on photosynthesis in green leaves where chloroplasts absorb solar energy because they contain the green pigment chlorophyll in thylakoid membranes. Mitochondria in plant and animal cells carry on cellular respiration, a process that produces ATP on the membranous invaginations called cristae.

carbohydrates to many molecules of ATP and uses them as a source of energy for individual reactions, such as linking amino acids during protein synthesis. Mitochondria are most abundant in human cells that carry out energy-intensive activities. For example, ATP provides the energy for muscle contraction and nerve conduction. Mitochondria are not as complex as chloroplasts but their inner membrane does fold back and forth, forming the cristae that act as shelves where ATP is formed. ATP exits mitochondria and enters the cytoplasm where it is utilized as an immediate energy source.

It is of great interest to scientists that both chloroplasts and mitochondria provide evidence that they were once free-living prokaryotes. For example, they have their own DNA in a nucleoid region, and they make some of their own proteins. For a more thorough discussion of this topic, see "How the Eukaryotic Cell Evolved" on this page.

▶ 4.9 CHECK YOUR PROGRESS

1. Describe how it is possible to trace the energy of the sun to ATP molecules.

HOW LIFE CHANGES *Application*

4C How the Eukaryotic Cell Evolved

Life's history is written in the fossil record, which includes the remains of past life, often encased by stone (see Section 16.1). The fossil record tells us that the prokaryotic cell was present about 3.5 BYA (billion years ago); the eukaryotic cell evolved in stages (Fig. 4C). The nuclear envelope and nucleus may have arisen around 2 BYA from an infolding of the plasma membrane, but what about the organelles such as mitochondria and chloroplasts? Much evidence supports the proposal that these organelles were once free-living prokaryotes that were either prey to or parasites of a eukaryotic cell. Their outer double membrane tells us that the eukaryotic cell engulfed them—the outer membrane is derived from the host plasma membrane, and the inner membrane was their own outer surface. By now, they are endosymbionts—organisms that live inside a host cell and are indispensable to their host, the cell that engulfed them.

Mitochondria and chloroplasts have their own DNA—circular like that of a prokaryote—and they carry on protein synthesis in the same manner as bacteria. Then, too, they reproduce by splitting as do bacteria, and their reproduction occurs independently of host cell reproduction.

The theory of endosymbiosis explains that because all cells have mitochondria, aerobic bacteria entered the host cell first, perhaps just when oxygen began to rise in the atmosphere due to the advent of photosynthesis by free-living cyanobacteria (see Fig. 17.11C). A host cell with an endosymbiont that used oxygen and produced ATP molecules would have been a distinct evolutionary advantage. Later, a cyanobacterium entered certain cells, and these cells became capable of photosynthesis. Being able to make your own food does away with the need to find it elsewhere. Eventually the relationship between host cells and endosymbionts became so beneficial that by now they cannot live separately from one another!

Animation Endosymbiosis

CONSIDER THESE QUESTIONS

1. Explain the phraseology "the host had an evolutionary advantage." Be sure to mention comparative number of offspring in your explanation.
2. If you compared the structure of a cyanobacterium with that of a chloroplast, what similarities would you expect to find?

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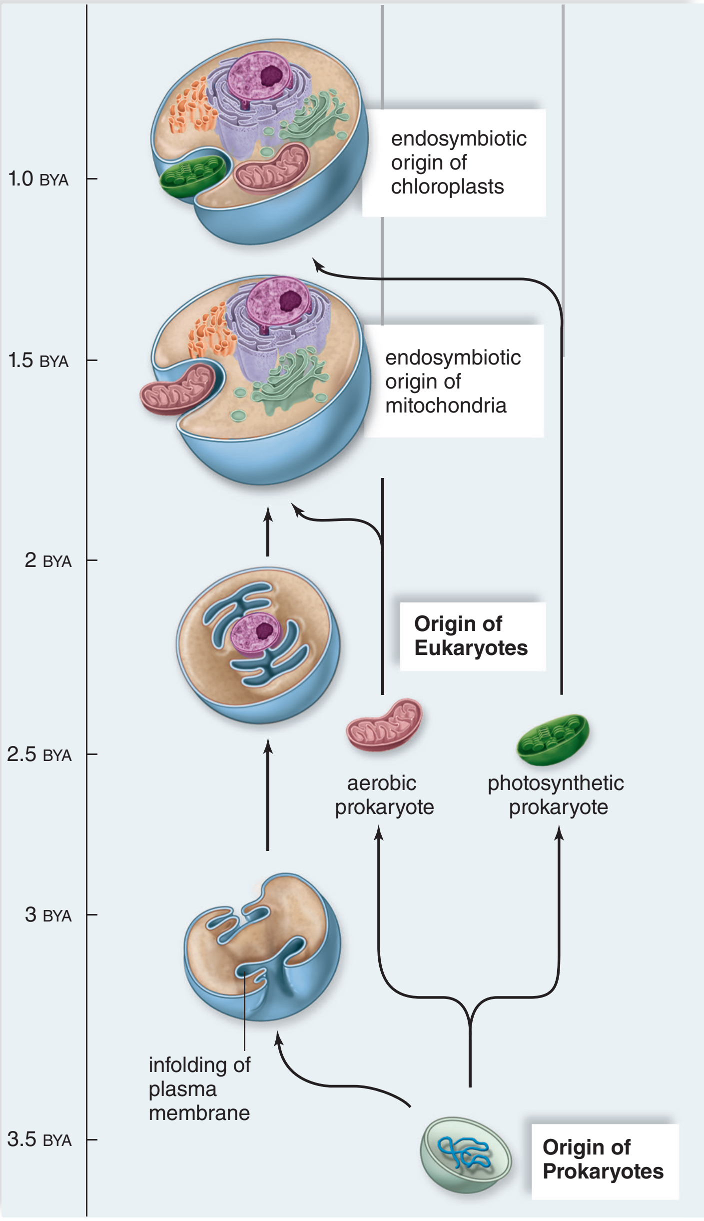


FIGURE 4C The eukaryotic cell was fully formed when a nucleated cell engulfed prokaryotes that became endosymbionts.

The Cytoskeleton and Cell Movement

As you know, bones and muscles give an animal structure and produce movement. Similarly, the fibers of the cytoskeleton maintain cell shape and cause the cell and its organelles to move. Cilia and flagella are also instrumental in producing movement, so they are included in this part of the chapter as well.

4.10 The cytoskeleton maintains cell shape and assists movement

LEARNING OUTCOMES

When you complete this section, you should be able to

1. Identify and contrast the structure and function of cytoskeletal fibers and flagella.
2. Describe the possible relationship between centrioles and flagella.
3. Understand that motor molecules enable cell parts and also cilia and flagella to move.

All eukaryotic cells have a **cytoskeleton,** a network of protein fibers within the cytoplasm. Even though both plant and animal cells have a cytoskeleton, most of our discussion pertains to an animal cell. The cytoskeleton (1) supports the animal cell and determines its shape. Remarkably, however, the protein fibers of the cytoskeleton can assemble and disassemble their subunits rapidly, and this accounts for why the shape of some animal cells can change from moment to moment. Similarly, the cytoskeleton (2) anchors the organelles in place but can also allow them to move, as when a vesicle moves from the Golgi to the plasma membrane. Because the cytoskeleton has the dual function of support and movement, it is appropriately described as the "skeleton and muscles" of an animal cell.

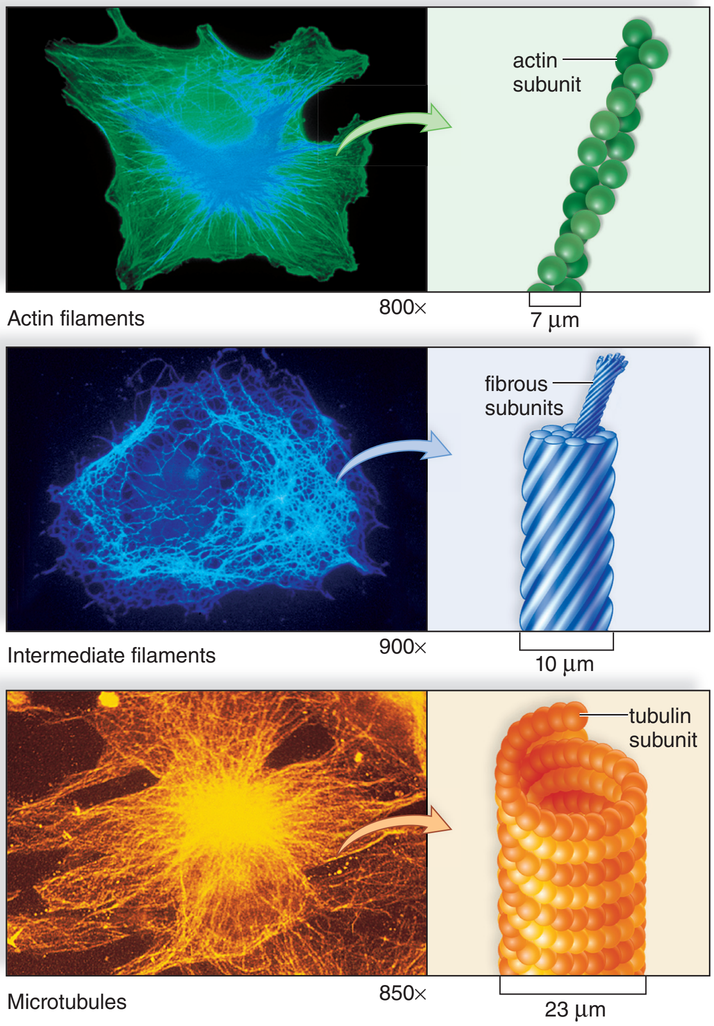
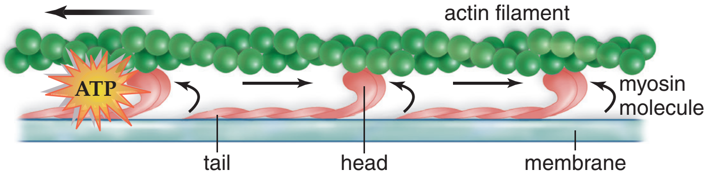


FIGURE 4.10A The cytoskeleton contains these three types of fibers that support the cell.

If you could look closely at the cytoskeleton in an animal cell, you would note the three different types of fibers shown in Figure 4.10A. Because you can't see these fibers with a light microscope, scientists prepare fluorescent antibodies, each of which attaches to only one type of fiber and then they photograph the cells under fluorescent light. Actin filaments and microtubules have binding sites for **motor molecules,** which are proteins able to break down ATP and use the resulting energy to change shape in order to move from one binding site to the next. Motor molecules are either kinesins, dyneins, or myosins. As they move along a cytoskeletal fiber, they pull their cargo (lysosomes, chromosomes, vesicles, etc.) with them.

Actin filaments are so named because they contain two twisted strands of actin, a fibrous protein. Bundles of actin filaments support the plasma membrane and other structures, such as the microvilli (short projections) of intestinal cells. However, you can primarily associate actin filaments with movement. For example, actin interacts with myosin when muscle contraction occurs. Just as you do when participating in a tug of war, a myosin head attaches, detaches, and reattaches further along an actin filament, and this pulls the actin filament in the opposite direction:



Also in conjunction with myosin, actin filaments act like purse strings to pinch off and separate cells during cell division. Then, too, they are responsible for the ability of white blood cells to crawl and to engulf disease-causing agents such as viruses and bacteria.

Intermediate filaments have a diameter that is intermediate between actin filaments and microtubules. Although the specific protein composition varies with the type of cell, intermediate filaments always have a ropelike structure that provides mechanical strength. Some intermediate filaments support the nuclear envelope, whereas others support the plasma membrane and take part in the formation of cell-to-cell junctions. Intermediate filaments made of the protein keratin strengthen skin cells.

Microtubules are cylindrical structures composed of 13 rows of a protein called tubulin. Assembly is under the control of a microtubule organizing center (MTOC) located in the **centrosome** (see Fig. 4.3A). Microtubules radiate from the centrosome, helping to maintain the shape of the cell and acting as tracks along which organelles can move (Fig. 4.10B). Before a cell divides, microtubules disassemble and then reassemble into a structure called a spindle, which distributes chromosomes in an orderly manner.

Cilia and Flagella Cilia and flagella (sing., cilium, flagellum) are whiplike projections of cells. **Cilia** move stiffly, like an oar, and **flagella** move in an undulating, snakelike fashion. Cilia are short (2–10 μm), and flagella are longer (usually no more than 200 μm). Unicellular protists utilize cilia or flagella to move about. The ciliated cells that line our respiratory tract sweep debris trapped within mucus back up into the throat, which helps keep the lungs clean. Similarly, ciliated cells move an egg along the oviduct, where it can be fertilized by a flagellated sperm cell (Fig. 4.10C, *left*).

A cilium and a flagellum have the same organization of microtubules within a plasma membrane covering (Fig. 4.10C, *right*). Dynein side arms, powered by ATP, allow the microtubules in cilia and flagella to interact and bend, and thereby to move.

A particular genetic disorder illustrates the importance of normal cilia and flagella. Some individuals have an inherited defect that leads to malformed microtubules in cilia and flagella. Not surprisingly, they suffer from recurrent and severe respiratory infections, because the ciliated cells lining their respiratory passages fail to keep their lungs clean. They are also infertile due to the lack of ciliary action to move the egg in a female, or the lack of flagellar action by sperm in a male.

Centrioles Located in the centrosome, **centrioles** are short, barrel-shaped organelles composed of microtubules. It's possible that centrioles give rise to **basal bodies,** which lie at the base of and organize the microtubules in cilia and flagella (Fig. 4.10C, *far right*). It's also possible that centrioles help organize the spindle, mentioned earlier, which is so necessary to cell division. However, plant cells lack centrioles in their centrosomes yet they do form a spindle during cell division.

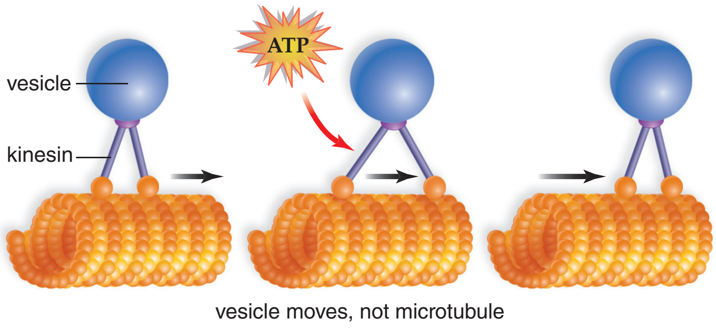
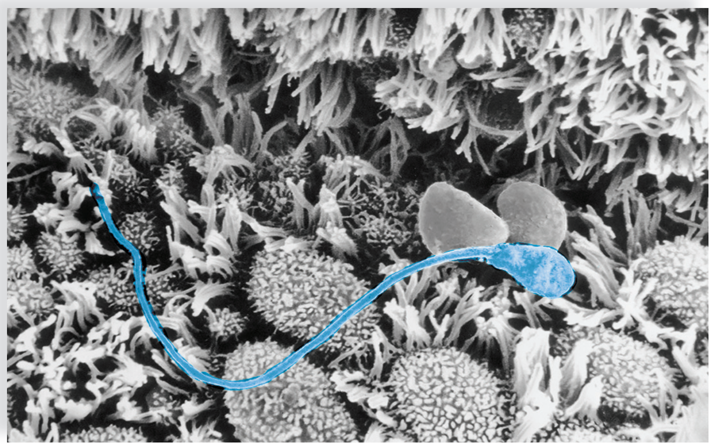


FIGURE 4.10B The motor molecule kinesin is moving a vesicle along a microtubule track.

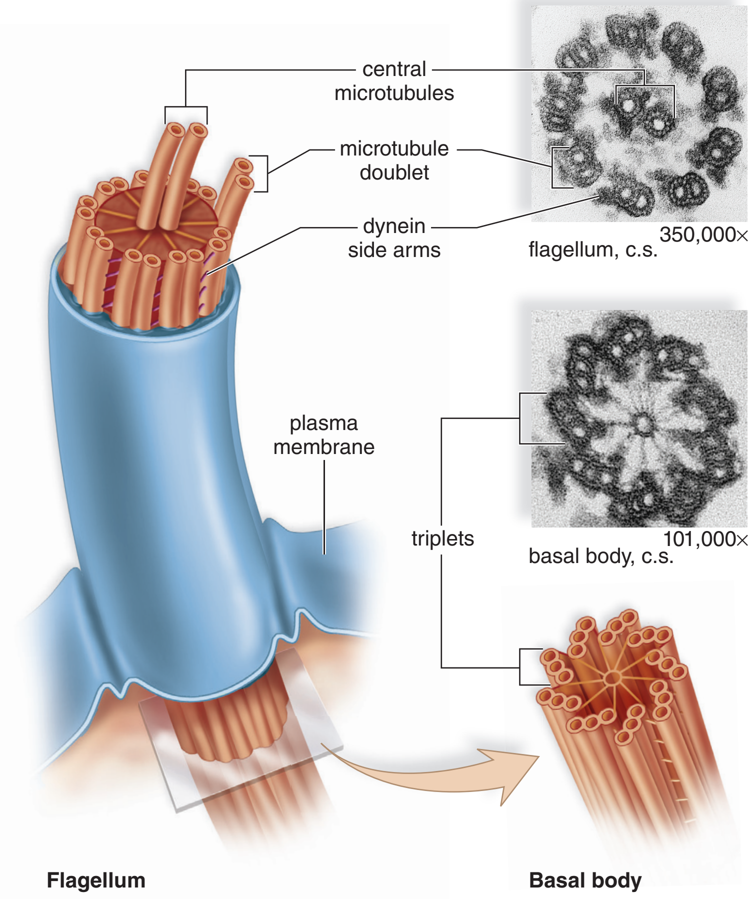
▶ **4.10 CHECK YOUR PROGRESS**

1. Identify with examples the two general functions of cytoskeletal fibers.
2. Compare the structure and function of actin filaments and microtubules.
3. Explain how motor molecules function to allow cell parts and flagella to move.

FIGURE 4.10C The motor molecule dynein and the microtubule organization in cilia and flagella allows these cellular projections that arise from basal bodies to move.

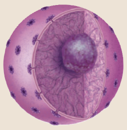
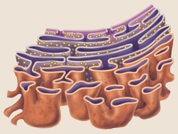
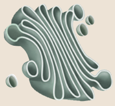
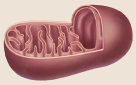
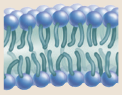
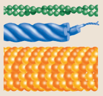


Flagellated sperm in oviduct lined by ciliated cells 7,200×



The Eukaryotic Cell in Review

TABLE 4.11 **Eukaryotic Cell Structures**

Cell Structure	Description	Function
Nucleus 	Enclosed by nuclear envelope with pores; contains nucleolus and chromatin where DNA is located	Controls cell because it houses genetic information; nucleolus produces ribosomal subunits
Ribosome 	Small particle having two subunits composed of RNA and protein	Produces proteins according to the coded information supplied by mRNA nucleotides
Endoplasmic reticulum (ER) 	Network of membranous tubules and flattened sacs Rough ER: studded with ribosomes Smooth ER: lacks ribosomes	 Produces proteins; forms transport vesicles Produces lipids; forms transport vesicles
Golgi Apparatus 	Stack of several flattened saccules	Carries out processing and packaging of proteins and lipids; forms secretory vesicles and lysosomes
Vesicle 	Tiny membranous sac containing cell products	Isolates and transports biomolecules
Vacuole 	Small to large membranous sac—plant cells have large central vacuole featured here	Stores varied biomolecules and wastes; in plant cells produces turgor pressure
Lysosome 	Vesicle produced by Golgi apparatus that contains hydrolytic digestive enzymes	Breaks down debris, large biomolecules, and even organelles
Peroxisome 	Vesicle with enzymes for varied functions	Breaks down fatty acids and poisons such as hydrogen peroxide
Chloroplast 	Enclosed by a double membrane; interior has membranous thylakoids that contain chlorophyll	Absorbs solar energy; carries on photosynthesis and produces carbohydrates
Mitochondrion 	Enclosed by a double membrane; inner membrane forms cristae	Carries on cellular respiration with the breakdown of carbohydrates to produce ATP
Plasma Membrane 	Phospholipid bilayer with embedded proteins	Regulates the passage of molecules into and out of cell
Cell Wall 	In plant cells, outer layer of cellulose	Helps maintain shape of a plant cell, protects and supports the cell
Cytoskeleton 	Network of actin and intermediate filaments and microtubules	Maintains cell shape, assists transport of organelles within cell
Flagella (and Cilia) 	Microtubule-containing cellular extensions	Move the cell; cilia move substances along its surface

THE CHAPTER IN REVIEW

CONNECTING THE CONCEPTS

Our knowledge of cell anatomy has in part been gathered by studying micrographs of cells. This has allowed cytologists (biologists who study cells) to arrive at a generalized picture of cells, such as those depicted for an animal and a plant cell in section 4.3. Eukaryotic cells, taken as a whole, contain several types of organelles, and the learning outcomes throughout the chapter suggest that you should know the structure and function of each one. A concept to keep in mind is that "structure suits function." For example, ribosomal subunits move from the nucleus to the cytoplasm; therefore, it seems reasonable that the nuclear envelope has pores. Finding relationships between structure and function will give you a deeper understanding of the cell and boost your memory capabilities.

Also, realizing that the organelles work together is helpful. If you wanted to describe the involvement of cell parts to make a protein, you would start with the nucleus because chromosomes contain DNA, which specifies the order of amino acids in a particular protein. From there, you would mention the ribosomes at the rough endoplasmic reticulum (RER), transport vesicles, the Golgi apparatus, and a possible final destination for the protein. Analogies can help you remember the structure and function of organelles. For example, the endomembrane system can be compared to a post office: Proteins (the letters) are deposited into the RER (the local post office), which sends them to a Golgi (the regional sorting center) from which they are sent to their correct destinations. The pulse-labeling technique, described in section 4B, provides evidence to support this analogy.

Table 4.11 suggests ways for you to group the organelle for study and understanding. Lysosomes and peroxisomes are vesicles with digestive functions: Lysosomes digest various biomolecules while peroxisomes break down lipids. The origin of the eukaryotic cell links together what you know about the structure of prokaryotic and eukaryotic cells because the endosymbiotic theory says that mitochondria and chloroplasts were once free-living prokaryotes.

In Chapter 5, we continue our general study of the cell by considering some of the functions common to all cells. For example, all cells exchange substances across the plasma membrane, and they also carry out enzymatic metabolic reactions, which either release or require energy.

ANALYZE AND EVALUATE

1. Use the structure of the prokaryotic cell to support the endosymbiotic theory.
2. Explain how the structure of the endoplasmic reticulum suits its function.
3. Microtubules are a part of the cytoskeleton and are found in cilia and flagella. What function of the cytoskeleton is consistent with the presence of microtubules in these structures?

SUMMARIZE

The Cellular Level of Organization

4.1 All organisms are composed of cells

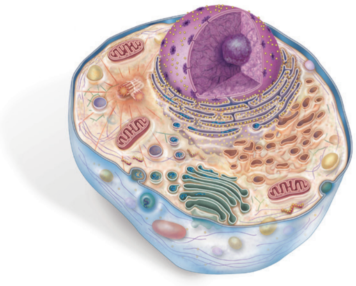
- The **cell theory** states the following:
  A cell is the basic unit of life.
  All organisms are made up of cells.
  New cells arise only from preexisting cells.
- Most cells are quite small (measured in micrometers). A small size gives them a **surface-area-to-volume ratio** that is large enough to allow adequate exchanges with the environment.

4.2 Prokaryotic cells evolved first

- **Prokaryotic cells** are classified in the domains **Archaea** and **Bacteria.** They are simpler in structure and much smaller than eukaryotic cells and lack a membrane-enclosed nucleus. The single chromosome is in a region called the **nucleoid.**
- Like all cells, prokaryotic cells have a **plasma membrane** surrounding a **cytoplasm** (semifluid interior). The prokaryotic cytoplasm contains plentiful **ribosomes,** protein-producing particles. In addition, prokaryotic cells are protected by a **cell wall** and a **capsule. Pili** allow bacteria to attach to solid substances.

4.3 Eukaryotic cells contain specialized organelles: An overview

- The cells of **eukaryotic organisms** in the domain **Eukarya** have a membrane-enclosed **nucleus** and **organelles,** which are structures specialized to perform specific functions. (See Figs. 4.3A and 4.3B.) The organization of eukaryotic cells allows them to be larger than prokaryotic cells.



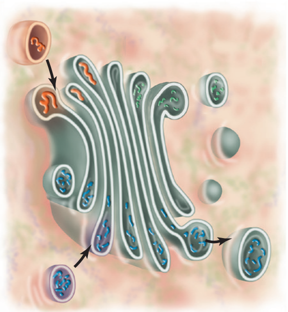
The Nucleus and the Endomembrane System

4.4 The nucleus is a control center

- The nucleus contains genes, composed of DNA, located within **chromatin** that becomes organized as **chromosomes** when nuclear division occurs. The **nucleolus** produces ribosomal subunits. The nucleus is enclosed by a double membrane called the **nuclear envelope** with **nuclear pores** that permit communication between the nucleus and the cytoplasm.
- The nuclear membrane is a part of the endomembrane system, which is composed of membranous structures that are either directly connected or communicate by way of transport vesicles.
- An RNA copy of a gene called messenger RNA (mRNA) exits the nucleus and attaches to a ribosome that then produces a protein. When the ribosome attaches to the **endoplasmic reticulum** (**ER**), the protein enters the ER where the protein takes on its final shape.

4.5 The ER produces and transports proteins and lipids to the Golgi apparatus

- The outer membrane of the nuclear envelope is directly connected to the endoplasmic reticulum, a system of tubules and flattened saccules (small sacs) that join and form one whole. The **rough ER** (**RER**) has attached ribosomes and therefore it produces proteins (rough ER); the **smooth ER** (**SER**) produces lipids.



- **Transport vesicles** from the ER carry proteins and lipids to the **Golgi apparatus,** a stack of flattened saccules which modify and package proteins and lipids for distribution. In the secretory pathway, transport vesicles leave the Golgi apparatus and travel to the plasma membrane, where **secretion** occurs.
- The Golgi apparatus also produces **lysosomes,** membranous vesicles that digest biomolecules and cell parts because they contain hydrolytic digestive enzymes. In the lysosomal pathway, lysosomes fuse with vesicles and digest any biomolecules or particles entering the cell by way of the plasma membrane.

4.6 The organelles of the endomembrane system work together

- The nuclear envelope, the ER, Golgi apparatus, lysosomes, and transport vesicles make up the **endomembrane system.** The nucleus and these organelles work together to produce proteins and lipids that function within the cell or are secreted for specific purposes in the organism. For example, they produce the proteins and lipids found in the plasma membrane and the regulatory proteins that leave the cell.

Vacuoles and Vesicles

4.7 Vacuoles are common in plant cells

- **Vacuoles,** like vesicles, are membranous sacs but they are larger in size and specialize in storage. Plant cells have a large **central vacuole** that stores watery cell sap and maintains **turgor pressure.**

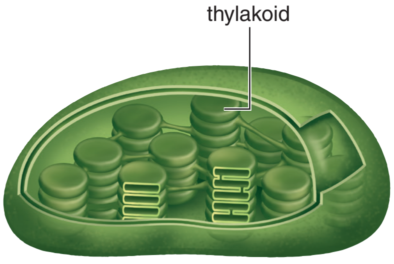
4.8 Peroxisomes have many different functions

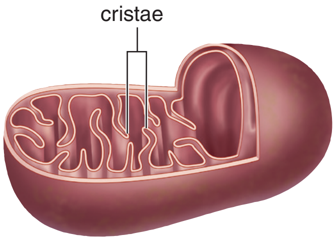
- **Peroxisomes** are vesicles that contain enzymes and when the concentration rises, the proteins crystallize. Unlike lysosomes, peroxisomes arise at the ER and absorb enzymes from the cytoplasm. They synthesize some substances and break down toxins such as hydrogen peroxide.

Chloroplasts and Mitochondria

4.9 Chloroplasts and mitochondria have opposite functions

- **Chloroplasts** have internal membranes called thylakoids, where chlorophyll absorbs solar energy and produces carbohydrates during **photosynthesis.**
- **Mitochondria** have membranous shelves called cristae, where **cellular respiration** converts carbohydrate energy into the energy of ATP molecules.





The Cytoskeleton and Cell Movement

4.10 The cytoskeleton maintains cell shape and assists movement

- The cytoskeleton is a network of protein fibers within the cytoplasm. **Actin filaments** are organized in bundles or networks. **Intermediate filaments** are ropelike assemblies of polypeptides. **Microtubules** are made of the globular protein tubulin. **Motor molecules** such as dynein move vesicles along microtubules. They act as tracks for organelle movement. The microtubule organizing center (MTOC) regulates microtubule assembly and is located in the **centrosome.**
- **Cilia** (short) and **flagella** (long) are whiplike projections from cells that allow the cell to move. Cilia and flagella grow from **basal bodies,** perhaps derived from **centrioles.**

The Eukaryotic Cell in Review

- See Table 4.11.

TEST YOURSELF

The Cellular Level of Organization

1. The cell theory states
   a. cells form as organelles and molecules become grouped together in an organized manner.
   b. the normal functioning of an organism depends on its individual cells.
   c. the cell is the basic unit of life.
   d. only eukaryotic organisms are made of cells.
2. When you examine a cell using a light microscope, which of these can you usually see?
   a. the nucleus only
   b. the nucleus and the nucleolus
   c. the nucleus, the nucleolus, and the threads of chromatin
   d. all of these plus the DNA double helix
3. The small size of cells best correlates with
   a. their ability to reproduce.
   b. their prokaryotic versus eukaryotic nature.
   c. an adequate surface area for exchange of materials.
   d. their vast versatility.
   e. All of these are correct.
4. Which of the following structures are found in both plant and animal cells?
   a. centrioles
   b. chloroplasts
   c. cell wall
   d. mitochondria
   e. All of these are found in both types of cells.
5. Eukaryotic cells compensate for a low surface-to-volume ratio by
   a. taking up materials from the environment more efficiently.
   b. lowering their rate of metabolism.
   c. compartmentalizing their activities into organelles.
   d. reducing the number of activities in each cell.
6. The cell wall and capsule of bacteria
   a. are located inside the plasma membrane.
   b. compensate for the lack of a plasma membrane.
   c. provide easy access to the cytoplasm.
   d. have projections called pili.
   e. Both b and c are correct.

The Nucleus and the Endomembrane System

7. What is synthesized by the nucleolus?
   a. mitochondria
   b. ribosomal subunits
   c. transfer RNA
   d. DNA
8. The organelle that can modify a protein and determine its destination in the cell is the
   a. ribosome.
   b. vacuole.
   c. Golgi apparatus.
   d. lysosome.
9. Which of these is not involved in protein production and secretion?
   a. smooth ER
   b. nucleus
   c. plasma membrane
   d. All of these are correct.

10. **THINKING CONCEPTUALLY** Communication is critical in cells. How does the nucleus communicate with the cytoplasm, and how does the rough ER communicate with the Golgi?
11. __________ are produced by the Golgi apparatus and contain __________.
    - a. Lysosomes, DNA
    - b. Mitochondria, DNA
    - c. Lysosomes, enzymes
    - d. Nuclei, DNA
12. Vesicles from the ER most likely are on their way to
    - a. the rough ER.
    - b. the lysosomes.
    - c. the Golgi apparatus.
    - d. the plant cell vacuole only.
    - e. the location suitable to their size.
13. Which organelle in the endomembrane system is incorrectly matched with its function?
    - a. Nucleus—contains genetic information regarding the sequence of amino acids in proteins
    - b. Transport vesicles—the way the nucleus communicates with the ER
    - c. Golgi apparatus—involved in modification and packaging of proteins
    - d. Lysosomes—digest biomolecules and cell parts
    - e. All of these associations are correct.
14. **THINKING CONCEPTUALLY** A concept is an encompassing idea tested by the scientific method. The concept of the endomembrane system is based on what data?

Vacuoles and Vesicles

15. The central vacuole of plant cells may contain
    - a. flower color pigments.
    - b. toxins that protect plants against herbivorous animals.
    - c. sugars.
    - d. All of these are correct.
16. Peroxisomes
    - a. are the same as lysosomes.
    - b. are made by the Golgi apparatus.
    - c. accumulate as we age.
    - d. contain enzymes involved in lipid metabolism.

Chloroplasts and Mitochondria

17. Mitochondria
    - a. are involved in cellular respiration.
    - b. break down ATP to release energy for cells.
    - c. contain stacks of thylakoid membranes.
    - d. are present in animal cells but not in plant cells.
    - e. All of these are correct.
18. The products of photosynthesis are
    - a. glucose and oxygen.
    - b. oxygen and water.
    - c. carbon dioxide and water.
    - d. glucose and water.
19. Why are mitochondria but not chloroplasts called the powerhouses of the cell?
    - a. Mitochondria form glucose, but chloroplasts break it down.
    - b. Mitochondria but not chloroplasts have their own genetic material.
    - c. Mitochondria but not chloroplasts capture solar energy.
    - d. Mitochondria but not chloroplasts directly provide ATP to the cell.
    - e. Both a and b are correct.
20. **THINKING CONCEPTUALLY** Both chloroplasts and mitochondria are critical to your existence. How so?

The Cytoskeleton and Cell Movement

21. Which of these are involved in movement of the cell or the cell contents?
    - a. actin filaments
    - b. microtubules
    - c. basal bodies
    - d. All of these are correct.
22. Which of these statements is not true?
    - a. Actin filaments are found in muscle cells.
    - b. Microtubules radiate from the ER.
    - c. Intermediate filaments sometimes contain keratin.
    - d. Motor molecules that are moving organelles use microtubules as tracks.
23. Plant cells lack centrioles, and this correlates with their lack of
    - a. mitochondria.
    - b. flagella.
    - c. a large central vacuole.
    - d. All of these are correct

The Eukaryotic Cell in Review

For questions 24–28, match the functions to the organelles in the key.

KEY:

- a. endoplasmic reticulum and Golgi apparatus
- b. peroxisomes and lysosomes
- c. chloroplast and mitochondria
- d. centrosome and microtubules
- e. nucleus and ribosomes

24. Carbohydrate metabolism resulting in ATP formation
25. Contain enzymes for breaking down substances
26. Protein formation and secretion
27. Protein production as DNA dictates
28. Movement of the cell and its parts

GET INVOLVED

1. Utilizing Palade's procedure, described on page 72, you decide to label and trace the base uracil. What type of molecule are you labeling, and where do you expect to find it in Figure 4B?
2. After publishing your study from question 1, you are criticized for failing to trace uracil from mitochondria. Why might you have looked for uracil in mitochondria, and what comparative difference between the nuclear envelope and the mitochondrial double membrane might justify your study as is?

MEDIA STUDY TOOLS

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Enhance your study of this chapter with interactive study tools, practice tests, and engaging animations. Also, ask your instructor about the resources available through ConnectPlus, which includes LearnSmart, a personalized adaptive learning program, and a media-rich eBook.

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BIOLOGY